NOTE: IGLD 85 used 1982-1988 water level data. This study used 1977-1983 water level data because the 1982-88 data were not available at time of the study.

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Analyses Performed by the National Geodetic Survey in Support of the Readjustment of the International Great Lakes Datum

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ABSTRACT

This paper describes the history of vertical datums used in the Great Lakes region and gives the progress to date by the National Geodetic Survey (NGS) in support of the new adjustment of the International Great Lakes Datum of 1980 (IGLD 80).

The purpose of this report is two-fold: (1) to document the analyses performed by NGS' Vertical Network Branch (VNB) in support of the IGLD 80 adjustment and (2) to provide information to determine the water-level station pairs which should be used as water-level transfer stations in IGLD 80 and the North American Vertical Datum of 1988 (NAVD 88).

To assist in identifying and documenting the impact of IGLD 80, NGS compiled a primary vertical control network using the latest U.S. and Canadian leveling data available. The network started at the mouth of the St. Lawrence and included leveling lines which surrounded the Great Lakes. Analyses of this network were helpful in determining additional releveling requirements and the magnitudes of height changes from the present International Great Lakes Datum of 1955 (IGLD 55).

A comparison of U.S. network adjusted heights and Canadian network adjusted heights showed good overall agreement. The difference between the adjusted heights using independent leveling data from Ft. Kent, Maine, to the west end of Lake Superior is only 6.3 cm. Some larger differences exist at intermediate points between the two end points, but this is to be expected in vertical network adjustments. This supports the importance of using a leveling network instead of single-route leveling lines to estimate the heights of bench marks.

An analysis of the latest available leveling data indicates that each lake surface approximates an eguipotential surface. However, on each lake there are some water-level

station values which appear to be too high or too low relative to the other station values on that lake. Mean water levels estimated at Thunder Bay (station 10050) and Grand Marais (station 9090), both on Lake Superior, differ by only 0.6 kgal-cm (approximately 0.02 ft), but the east and west ends of the lake differ by 17.4 kgal-cm (approximately 0.57 ft), with the west end higher than the east end.

The results given in this report provide the information required to select specific water-level station pairs to generate zero geopotential difference observations. These observations will be included in both the NAVD 88 and IGLD 80 networks. IGLD 80 should be the same as NAVD 88 except a constant offset for the difference between local mean water level at Rimouski and the corresponding published NAVD 88 geopotential number at Rimouski may be required. Geopotential numbers from NAVD 88 should be used because they will provide the best estimate of hydraulic head.

HISTORY OF GREAT LAKES VERTICAL CONTROL NETWORKS

A detailed report on the history of the vertical control networks used in the Great Lakes region can be found in a report by Lippincott (1985). The following is a summary from Lippincott's 1985 report.

Levels of 1877

In 1841, the U.S. Congress appropriated funds to survey the northern and northwestern lakes of the United States. The Corps of Engineers (COE) established the U.S. Lake Survey (USLS) to perform the surveys. By 1860, leveling surveys were underway and some water-level data were already being used to determine relative changes on each lake. By 1875, sufficient leveling observations existed to connect Oswego Harbor on Lake Ontario to local mean sea level in New York City, Lake Ontario to Lake Erie, and Lake Erie to Lake Huron. In 1876, leveling was performed between Escanaba on Lake Michigan and Marquette on Lake Superior.

In 1877, the leveling and water-level data were used to establish the vertical datum on each of the Great Lakes. This adjustment was called the "Levels of 1877."

Water-Level Transfers

The water-level transfer procedure has been used to establish vertical datums on the Great Lakes since 1875. The procedure assumes that the mean water surface estimated at one location on a lake is equal (during a certain period of time) to another location on the same lake. Fig. 1 depicts the water-level transfer concept. Leveling data are used to estimate the height difference between the "zero" mark on the staff and a reference bench mark. Mean water-level gauge readings are used to determine the elevation of the lake level at a particular site as referenced to the zero mark on a particular staff. This is performed at two or more gauge sites on the same lake. It is then assumed that the two mean water surfaces represent the same potential surface. Therefore, an observation of zero geopotential difference can be made.

U.S Lake Survey 1903 Datum

By 1902, USLS releveled all its Great Lakes lines. In 1903, the U.S. Coast and Geodetic Survey (now called the National Ocean Service) performed a network adjustment which included the USLS leveling lines and several water-level transfers. The 1903 network adjustment results were adopted by USLS. Using additional leveling data and water-evel transfers, the remaining bench marks on the Great Lakes network were incorporated into a new network which was called the "U.S. Lake Survey 1903 Datum" or the "1903 Datum."

Adjustment of 1935

By 1933, almost every U.S. harbor on the Great Lakes had a water-level gauge. An adjustment using the latest leveling and water-level transfer data was performed in 1936. This adjustment was called the "Adjustment of 1935" or the "1935 Datum."

A new mean sea level connection was not established in 1935; therefore, USLS held a few adjusted heights from the 1903 adjustment, i.e., one adjusted height on Lake Ontario (Oswego), one on Lake Erie (Cleveland), and one on Lake Huron (Harbor Beach).
New elevations on Lake Superior were determined using a water-level transfer from Harbor Beach to DeTour and leveling from DeTour to Point Iroquois.

International Great Lakes Datum of 1955 (IGLD 55)

In 1953, USLS and its Canadian counterpart initiated a program of coordinating basic hydraulic and hydrologic data in the Great Lakes area. The Canadian agencies used heights referenced to the 1903 Datum, while the U.S. used heights referenced to the 1935 Datum. These differences were small, but did cause some confusion. The International Coordinating Committee decided that a joint international Great Lakes Datum should be established. This led to the International Great Lakes Datum of 1955 (IGLD 55).

IGLD 55 used water-level transfer data from the period 1952-58. A first-order leveling line was performed along the St. Lawrence River from Point-au-Pere (Fathers Point), Quebec, to Kingston, Ontario. The United States leveled along the U.S. side of the river and made several ties along the border. Once again, leveling observations were performed between lakes and water-level transfer observations were made between stations on each lake. Fig. 2 depicts the 1955 network.

The datum for IGLD 55 was determined by holding the elevation of local mean water level fixed at Point-au-Pere. Normal dynamic elevations, i.e., dynamic elevations using normal gravity values, were adopted as the elevations to be used and published for IGLD 55. According to Lippincott (1985), the primary reason for adopting dynamic elevations for the new datum was to provide a means for the more accurate measurement of potential hydraulic head between points.

HEIGHT SYSTEMS RELEVANT TO IGLD 80

There are several different height systems used by the surveying and mapping community. Two of these height systems are relevant to the IGLD 80 study: orthometric heights and dynamic heights. Geopotential numbers relate these two systems to each other.

A geopotential number (C) of a bench mark is the difference in potential measured from the reference geopotential surface to the equipotential surface passing through the mark. It is the amount of work required to raise a unit mass of 1 kg against gravity through the orthometric height to the mark. Geopotential differences are differences in potential which indicate hydraulic head.

An orthometric height of a mark is the distance from the reference surface to the mark, measured along the line perpendicular to every equipotential surface in between. A series of equipotential surfaces can be used to represent the gravity field. One of these surfaces is specified as the reference system from which orthometric heights are measured. These surfaces defined by the gravity field are not parallel because of the rotation of the Earth and gravity anomalies in the gravity field. Two points, therefore, could have the same potential but may have two different orthometric heights. The value of the orthometric height at a point depends on all the equipotential surfaces beneath that point.

The orthometric height (H) and the geopotential number (C) are related through the following equation:

$$C = G * H,$$

where G is the gravity value estimated for a particular system. Height systems are called different names depending on the G selected. When G is computed using the Helmert height reduction formula (Helmert 1890), which is what was used in this study, the heights are called Helmert orthometric heights; when G is computed using the International formula for normal gravity, the heights are called normal orthometric heights; and when G is equal to normal gravity at 45 degrees latitude equals 980.6294 gals. Therefore dynamic heights are also an estimate of hydraulic head. In other words, points that have the same geopotential number will have the same dynamic height.

The IGLD 55 is a normal dynamic height system which uses a computed value of gravity based on the International formula for normal gravity. Today, there is sufficient observed gravity available to estimate "true" geopotential differences instead of "normal" geopotential differences. The "true" geopotential differences will more accurately estimate hydraulic head.

ANALYSES OF IGLD 80 PRIMARY VERTICAL CONTROL NETWORK

NGS' Vertical Network Branch has undertaken a special study to compile a Canadian and

U.S. primary vertical control network using the latest leveling data available in the Great Lakes region. (See fig. 3.) Analyses of these networks were helpful in determining the effects of the datum constraint and the magnitudes of height changes from IGLD 55.

Most of the data involved in the study were observed between the years 1965 and 1986. The primary network consisted of 78 loops containing 1,119 bench marks. Each loop is composed of links based on the latest leveling data connecting the junctions of loops. The network connected to 50 water-level stations along the Great Lakes.
In addition, 25 connections were made between the Canadian and U.S. vertical control networks.

The U.S. leveling observations were corrected for rod scale, rod temperature, level collimation, astronomic, refraction, and magnetic effects (Balazs and Young 1982, Holdahl et al. 1986). These corrections are applied to observed leveling data to minimize the effects of known systematic errors. The rod scale correction ensures a uniform scale which conforms to the National length standard. The rod temperature correction accounts for variation in the length of the leveling rod's Invar strip which results from temperature changes.

The level collimation correction minimizes the error caused by nonhorizontality of the leveling instrument's line of sight for unequal sight lengths. The refraction correction is modeled to minimize the refraction error caused by temperature (density) variation of air strata. The astronomic correction counteracts the effects of the Moon and Sun on the equipotential surfaces of the Earth (Balazs and Young 1982).

The error due to magnetic fields in some automatic compensator-type leveling instruments, e.g., the Zeiss Ni-1, reach significant proportions when leveling in a north-south direction. The error is caused by residual magnetic sensitivity of the compensator's Invaralloy suspension tapes and degrades Zeiss Ni-1 performance more than other instruments because of its high mechanical tilt amplification (Gebler 1983, Leitz 1983, and Rumpf 1983). NGS established 30 magnetic correction constants for 23 compensators belonging to 17 instruments (Holdahl et al. 1986).

The orthometric correction eliminates the effect of the nonparallelism of equipotential surfaces. All geopotential differences were generated and validated, using gravity values derived from a Society of Exploration Geophysicists 4-kilometer gridded Bouguer anomaly data set. Therefore the orthometric correction was not applied to the observed differences.

As shown in fig. 3, approximately one-half of the vertical control network used in this study was generated from Canadian leveling data. Mr. F. W. Young, Geodetic Survey Division of Canada, provided NGS with uncorrected, observed geodetic leveling height differences in computer-readable form and sketches depicting the junction bench marks. The Canadian data involved in the IGLD 80 study were also influenced by magnetic effects. The Canadian Geodetic Survey Division performed a preliminary study documenting the effects of magnetic error on their leveling instruments (PVCS 1988). The study estimated the average magnetic constant to be -3.37 mm/km Gauss, which is similar to the average value of -3.68 mm/km Gauss determined by NGS (Holdahl et al. 1986). The -3.37 mm/km Gauss value was used to estimate the magnetic correction in the Canadian data. No other corrections were applied to the Canadian data because they were not available.

The water-level transfer data for the period 1977-83 were provided by Mr. H. A. Lippincott, U. S. National Ocean Service, and Mr. D. A. St. Jacques, Canadian Hydrographic Service. These differences were used to generate observed height differences from the primary bench mark at the gauge site to the mean water level (MWL) surface. The MWL surface at each water-level station was treated as if it were a monumented bench mark. In this way, the data were used to estimate geopotential numbers at all water-level stations.

Loop misclosures were computed and checked against allowable tolerances. Geopotential differences were used as observations in the least squares adjustment, geopotential numbers were solved for as unknowns, and orthometric heights were computed using the well known Helmert height reduction (Helmert 1890); $H = C/(g + 0.0424H)$, where C is the estimated geopotential number in geopotential units (gpu), g is the gravity value at the bench mark in gals, and H is the orthometric height in km. The weight of an observation was calculated using the formula I/(variance of the observation), where the variance of the observation is equal to ((a priori standard error **2 X kilometers of leveling)/(number of runnings)). The a priori standard errors for the orders and classes of leveling (FGCC 1984) used in the vertical network are listed below:

first-order, class 0 = 0.7 mm,
first-order, class I = 1.1 mm,
first-order, class II = 1.4 mm, and
second-order, class 0 = 3.0 mm.

Heights of bench marks were computed using a least squares adjustment. Data outliers were detected and removed during this analysis. Two links were rejected because of larger than expected misclosures. Tables 1 and 2 present some general statistics obtained during these analyses.

Results of Loop Analyses

After all geopotential differences were generated and validated, loop misclosures were computed and checked against allowable tolerances. Table 1 lists some general statistics about the loop closures obtained in this study. Fig. 2 shows the links which were rejected to reduce the effects of data outliers on the adjusted heights. These links are being investigated to determine why they disagree with surrounding data. Some of these leveling lines are scheduled to be releveled during the NAVD 88 releveling program.

Table 1.—Summary of statistics from loop misclosure analysis.

	No. of Loops in Final Network	No. of Loops Outside Allowable	No. of Links Rejected
U.S Network Only	24	3	2
Canadian Network Only	28	0	0
U.S. and Canadian Network	78	3	2

Results of Adjustment Analyses

After all loop misclosures were analyzed, bench mark heights were computed using a minimum-constraint least squares adjustment. Two links were rejected because of large residuals and large loop misclosures.

The adjustments performed were minimum-constraint least squares adjustments holding fixed the ge(opotential number of a bench mark, referenced to a zero value of the local mean water level at Point-au-Pere. This bench mark, 78KM066, was selected as the constraint because it was the bench mark/ised in the IGLD 55 datum definition.
The potential number, 3.434_kgal-m, was used because that is the IGLD 80 dynamic height of (78K0066 under the proposed IGLD 80 datum definition, i.e., the proposed IGLD 80 dynamic height of bench mark 1250 G at Rimouski is 6.283 m and the dynamic height difference between 1250 G and 78K0066 is 2.849 m. This is equivalent to holding Rimouski, because its value was determined from Point-au-Pere. The adjustment process estimated geopotential numbers and computed Helmert orthometric heights using the adjusted geopotential numbers and gravity values based on observed gravity data. The heights, however, were all reduced to a common height system before being compared.

Three separate adjustments were performed. Each adjustment was performed holding the elevation of a bench mark referenced to local mean water level fixed at Point-au-Pere (which was referenced to Rimouski). First, all U.S. data were combined into a network and an adjustment was performed on these data, this is denoted as the U.S. network throughout the paper; second, the Canadian network was formed and an adjustment was performed on these data, this is denoted as the Canadian network; lastly, the U.S. and Canadian data were combined into one network and an adjustment was performed on this set of data, this is denoted as the U.S. - Canadian network. A comparison of the differences between the U.S and Canadian border junction bench marks adjusted heights, the differences between IGLD 55 and preliminary IGLD 80 values, and estimated heights of MWL surfaces based on the leveling data are discussed.

Table 2.—Summary of statistics from minimum-constraint least squares adjustments.

	No. of Bench Marks	No. of Obs.	No. of Obs. Rejected	Std. Error Degrees of Unit Weight	Degrees of Freedom
U.S. Network	746	774	2	1.8	29
Canadian Network	529	559	0	1.2	31
U.S. - Canadian Network	1,119	1,206	2	1.5	88

Table 2 above lists some general statistics from the minimum-constraint least squares adjustments. Figs. 4 through 28 present more specific details from the results of the adjustments which will be addressed in the remaining sections of this report.

Comparison of Adjusted Heights Between U.S. and Canadian Networks

Fig. 4 is a map showing the differences between the U.S. network adjusted heights and the Canadian network adjusted heights. The two networks were equated at a junction bench mark near Ft. Kent, Maine.
The overall agreement between the two set of adjusted heights is excellent. The difference between the adjusted heights estimated using independent leveling data from Ft. Kent, Maine, to the west end of Lake Superior is only 6.3 cm. Some larger differences exist at intermediate points between the two end points, but this is to be expected in vertical network adjustments. These local disagreements are currently being investigated.

For example, there is a large difference in the two sets of adjusted heights between the northern and southern ends of Lake Huron, i.e., -7.0 cm. This, however, is a very large distance. Lake Huron itself is 400 km in length and the leveling distance is even more. Also, the Canadian data in this area contain magnetic error. An average magnetic constant was used to compute the magnetic correction for the Canadian data. If the observed leveling differences in this region are being overcorrected due to the magnetic correction, it would make Canadian heights higher at the northern end of the lake.
Portions of these data are being reobserved and should be available for analysis in early 1990.

This supports the importance of using a leveling network instead of single leveling lines to estimate the heights of bench marks. As a matter of fact, when additional data are added to the network, the overall difference decreases to less than 1 cm (see fig. 5). The larger vertical control network shown in fig. 5 was generated in support of the North American Vertical Datum of 1988 (NAVD 88) datum definition study (Zilkoski et al. 1989). NAVD 88 will be discussed in more detail later in this report.

Estimates of Mean Water Level (MWL) Using Separate U.S. and Canadian Networks

Figs. 6-11 show the estimates of MWL values obtained from separate least squares adjustments of the U.S network and Canadian network.
The geopotential numbers of MWL at stations on the Canadian side of the lakes were estimated using the Canadian data only and, similarly, the geopotential numbers of MWL at stations on the U.S. side were estimated using U.S. data only. MWL at Kingston (station 13988 on fig. 6) and Cape Vincent (station 2000 on fig. 6) were set equal; therefore, the MWL values are all relative to the east end of Lake Ontario. The value 73.489 kgal-m is the geopotential number of MWL at Kingston, estimated using the Canadian network.

If the leveling and water-level gauge data were free of error and the lake surface represented a true equipotential surface, then all the MWL values estimated on each lake should be equal. From figs. 6-11 it is obvious that the data contain some errors and/or the lake surfaces are not "true" equipotential surfaces everywhere. One purpose of this study was to determine which MWL station pairs on each lake represent zero geopotential differences and therefore should be included in the network adjustment as water-level transfer observations.

There are a few interesting items shown on figs. 6-11 which should be noted. Most of the MWL values on Lake Ontario indicate that the lake appears to be an equipotential surface. The western end of the lake, however, appears to be higher. (See fig. 6.) All estimates of MWL values from Kingston to Cobourg on the Canadian side and Cape Vincent to Olcott on the U. S. side indicate that the surface of the lake is practically the same. MWL values at Toronto, Burlington, and Port Weller appear to be too large relative to the other station values.

Fig. 7 shows the estimates of MWL values for Lake Erie. The overall difference from Buffalo (station 3020) to Toledo (station 3085) is only 2.4 kgal-cm (approximately 0.08 ft). [NOTE: In several sections of this report, the differences in MWL values are given in units of kgal-cm and converted to feet. From the previous section on height systems it should be clear that kgal-cm units cannot be directly converted to feet. However, for those readers that feel more comfortable using feet instead of kgal-cm, the meter to feet conversion of 3.2808333... was used to obtain an approximate value in feet. Whenever the units are kgal-cm and the value in parenthesis is in feet, the reader must remember that this is only an approximate value; the word approximately has been dropped.]

Although the overall difference between Buffalo and Toledo is small, there are a few large differences at other points on the lake. Cleveland (station 3063) appears to be much higher (171.220 kgal-m) than the rest of the lake level. A closer analysis of the leveling and water-level data between Cleveland and Erie (station 3038) indicates that the leveling data between Cleveland and Fairport may contain a blunder of 3 to 5 cm. Correcting the blunder would reduce the leveling height difference between Cleveland and Erie by 3-5 cm, which would make the MWL values estimated at Marblehead (station 3079) and Erie more consistent with each other. This would support the statement that wind is causing water to pile up at the Cleveland station.

NGS' Vertical Network Branch and the Ohio Department of Transportation (ODOT) are planning a special cooperative geodetic leveling/workshop project to relevel the segment between Cleveland and Fairport. A separate report will be prepared in early 1990 after the releveling has been performed and analyzed. Another item from fig. 7 is that MWL at Kingsville (station 12065) and Toledo (station 3085) differ by only 0.2 kgal-cm (0.007 ft).

Fig. 8 shows the differences between MWL estimates on Lake Clair. This lake is also part of the Great Lakes system. The two values differ by only 2.0 kgal-cm (0.07 ft).

The heights of MWL on Lake Huron are depicted in fig. 9. There is a large difference, 5.3 kgal-cm (0.17 ft) between Lakeport (station 5002) and Goderich (station 1160). The difference, however, between Harbor Beach (station 5014) and Goderich is less, only 3.4 kgal-cm (0.11 ft). The overall difference in MWL estimates between the northern and southern ends of the lake is small when using the results of either network adjustment by itself. That is, on the U.S. side from Lakeport to DeTour (station 5099) the difference in MWL values is 1.6 kgal-cm (0.05 ft) and on the Canadian side from Goderich to Thessalon (station 11070) the difference is 3.9 kgal-cm (0.13 ft).

As mentioned above, the Canadian data in this area contain magnetic error and an average magnetic constant was used to compute the magnetic correction. If the correction is overcorrecting in this region, then the estimated MWL value at Thessalon would be higher than its true value. Once again, the magnetic correction will be reevaluated for the data in this area after the releveling of these leveling lines has be completed and processed.

Fig. 10 gives the estimates of MWL values for Lake Michigan. From Calumet Harbor (station 7044) to Port Inland (station 7096), the MWL values differ by only 3.1 kgal-cm (0.1 ft). Port Inland and Mackinaw City (station 5080 on Lake Huron) differ by only 1.3 kgal-cm (0.04 ft). There are some larger anomalies, i.e., the MWL values at Green Bay (station 7078) and Sturgeon Bay Canal (station 7072) are higher than the rest of Lake Michigan.

The MWL estimates on Lake Superior (fig. 11) are probably the most interesting of all the lakes. First, the water-level surfaces at Thunder Bay (station 10050) and Grand Marais (station 9090) differ by only 4.2 kgal-cm (0.14 ft) This is very encouraging because these two values are estimated using independent networks and are relative to the east end of Lake Ontario. In addition, the MWL value at Grand Marais is 17.4 kgal-cm (0.57 ft) higher than the MWL value at Pt. Iroquois (station 9004), and the MWL value at Thunder Bay is 17.2 kgal-cm (0.56 ft) higher than the MWL value estimated at GROS Cap (station 10920). There also appears to be a systematic increase in MWL going from the east end to the west end of the lake. This would indicate either that the two networks contain similar systematic errors or that the lake has a one-half foot tilt in its water-level surface, with the western end of the lake being higher.

NGS is currently investigating if there is movement that is influencing the leveling data surrounding Lake Superior. It is possible that movement at junction bench marks between leveling lines of different epochs could be causing the estimates of MWL values to appear higher in the west.

In order to evaluate the differences between estimates of MWL on each lake, differences of MWL values relative to a datum point on each lake were computed. Figs. 12-17 list, for each lake, the differences in estimates of mean water level at each water-level station relative to one station on that lake. Once again, the heights of MWL at the stations on the Canadian side of the lake were estimated using Canadian data only and, similarly, the values of MWL estimated at stations on the U.S. side were estimated using U.S. data only. The mean water level at Kingston was assumed to be equal to the mean water level at Cape Vincent.

Figs. 12-17 were derived from the values given on figs. 6-11. The only difference is that a bias factor, which was different from lake to lake, but the same for all water-level stations on a particular lake, was subtracted from each MWL estimate. The value of the bias factor for each lake depended on which station was held fixed as a "datum point," e.g., fig. 13 shows that station Buffalo was held as the datum point, so its difference is equal to 0.0. This will be true for all datum points. Fig. 13 also shows that MWL value at Kingsville (station 12065) is 2.6 kgal-cm (0.09 ft) higher than MWL value at Buffalo.

Figs. 12-17 should be helpful in determining which water-level station pairs should be used to create water-level transfer observations of zero geopotential difference, as well as indicating leveling data which may contain errors.

Estimates of Mean Water Level Using the Combined U.S. - Canadian Network

The next part of the study was to analyze the estimates of MWL values based on the geopotential numbers obtained from the combined U.S. - Canadian leveling network adjustment. (See figs. 18-23.) The adjustment was a minimum-constraint least squares adjustment holding fixed the geopotential number of a bench mark, referenced to a zero value of the local mean water level, at Point-au-Pere. All estimates of MWL values are given in kgal-m and are relative to Point-au-Pere.

From figs. 18-23 there does not appear to be any surprises. The results of the two independent network adjustments generally showed good agreement, so the combined network adjustment process basically averaged the differences. There are a few items which deserve to be noted on figs. 18-23. First, the MWL value at stations Kingston (station 13988) and Cape Vincent (station 2000), shown on fig. 18, differ by only 1.5 kgal-cm (0.05 ft). Port Stanley (station 12400) and Erie (station 3038), shown on fig. 19, have exactly the same MWL value. The MWL values estimated at DeTour (station 5099) and Thessalon (station 11070), shown on fig. 21, differed by only 2.2 kgal-cm (0.07 ft), while the estimates from independent networks adjusted separately differed by 7.6 kgal-cm (0.25 ft). Lastly, MWL estimated at Thunder Bay (station 10050) and Grand Marais (station 9090), shown on fig. 23, differ by only 0.6 kgal-cm (0.02 ft); but, the west and east ends of the Lake differ by 17.4 kgal-cm (0.57 ft), the west end being higher than the east end.

Whenever MWL estimates appear to be "close" to the same value and it is believed that the stations should be on the same water level, then a water-level transfer observation of zero geopotential difference should be included in the network. This will strengthen the network if an appropriate weighting scheme is known and used. Whenever the differences between water-level values seem too "large," the leveling data should not be forced to fit the assumption that the water surface as measured by the water-level gauge data is an equipotential surface everywhere on the lake; unless it is known that the water level as measured by a pair of water-level stations should be equal and that the leveling data are suspected of containing errors. In that case, a water-level transfer observation of zero geopotential difference should be added to control the errors in the leveling data and to strengthen the network. The task of determining which water-level station pairs should be included as water-level transfer observations still needs to be completed.

Differences Between Preliminary IGLD 80 and Published IGLD 55

From the discussions presented above, it is obvious that the preliminary IGLD 80 values are different than the published IGLD 55 values. The question usually asked is, how much do the new values differ from the old ones? Figs. 24-29 and tables 3 and 4 give some differences in dynamic heights between preliminary IGLD 80 and published IGLD 55. The IGLD 80 adjusted geopotential numbers of the stations were estimated using the combined U.S. and Canadian network. The geopotential numbers were converted to dynamic heights before being compared with IGLD 55 published dynamic heights.

These differences should not be used to estimate vertical movement of bench marks because the differences are due to many factors, such as different network designs between IGLD 55 and IGLD 80, better estimates of corrections applied to account for systematic errors, and estimating geopotential differences using real gravity instead of using normal gravity. There is a constant bias of 0.020 m (approximately 0.066 ft) between IGLD 80 and IGLD 55 due to differences in datum definitions. It should be noted that the IGLD 80 geopotential differences are better estimates of hydraulic head than IGLD 55 dynamic height differences.

Table 3.--Differences between preliminary IGLD 80 and published IGLD 55 at U.S. sites.

	Station Number	Station Name	Dynamic IGLD 80 (m)	Heights IGLD 55 (m)	Differences in Heights (cm)	(ft)
Lake Ontario	2000	Cape Vincent	77.041	76.893	14.8	0.49
	2030	Oswego	77.468	77.329	13.9	0.46
	2058	Rochester	76.776	76.651	12.5	0.41
	2076	Olcott	77.712	77.588	12.4	0.41
Lake Erie	3020	Buffalo	179.504	179.337	16.7	0.55
	3028	Sturgeon Pt.	179.542	179.370	17.2	0.56
	3032	Barcelona	177.021	176.842	17.9	0.59
	3038	Erie	174.900	174.748	15.2	0.50
	3053	Fairport	175.908	175.743	16.5	0.54
	3063	Cleveland	178.826	178.593	23.3	0.76
	3079	Marblehead	179.277	179.090	18.7	0.61
	3085	Toledo	176.262	176.082	18.0	0.59
Lake St. Clair	4052	St. Clair Shores	176.968	176.779	18.9	0.62
Lake Huron	5002	Lakeport	183.402	183.196	20.6	0.68
	5014	Harbor Beach	177.569	177.363	20.6	0.68
	5035	Essexville	179.143	178.962	18.1	0.59
	5059	Harrisville	178.786	178.567	21.9	0.72
	5080	Mackinaw	178.147	177.859	28.8	0.95
	5099	DeTour	186.811	186.524	28.7	0.94
Lake Michigan	7023	Ludington	177.656	177.458	19.8	0.65
	7031	Holland	177.697	177.487	21.0	0.69
	7044	Calumet Harbor	177.997	177.795	20.2	0.66
	7057	Milwaukee	181.806	181.586	22.0	0.72
	7068	Kewaunee	177.867	177.587	28.0	0.92
	7072	Sturgeon Bay	178.560	178.287	27.3	0.90
	7078	Green Bay	178.807	178.507	30.0	0.98
	7096	Port Inlet	178.785	178.503	28.2	0.93
Lake Superior	9004	Pt. Iroquois	189.478	189.166	31.2	1.02
	9018	Marquette	188.975	188.612	36.3	1.19
	9044	Ontanagon	185.489	185.071	41.8	1.37
	9064	Duluth	184.485	184.068	41.7	1.37
	9070	Two Harbors	186.948	186.523	42.5	1.39
	9090	Grand Marais	185.040	184.583	45.7	1.50

Table 4.—Differences between preliminary IGLD 80 and published IGLD 55 at Canadian sites.

	Station Number	Station Name	Dynamic IGLD 80 (m)	Heights IGLD 55 (m)	Differences in Heights (cm)	(ft)
Lake Ontario	13988	Kingston	76.610	76.469	14.1	0.46
	13590	Cobourg	76.455	76.360	9.5	0.31
	13320	Toronto	76.989	76.849	14.0	0.46
	13150	Burlington	76.771	76.652	11.9	0.39
	13030	Port Weller	78.595	78.452	14.3	0.47
Lake Erie	12865	Port Colborne	175.909	175.754	15.5	0.51
	12710	Port Dover	175.763	175.597	16.6	0.54
	12400	Port Stanley	175.700	175. 543	15.7	0.52
	12250	Erieau	175.338	175.172	16.6	0.54
	12065	Kingsville	175.396	175.198	19.8	0.65
Lake St. Clair	11965	Belle River	176.597	176.399	19.8	0.65
Lake Huron	11860	Goderich	184.337	184.080	25.7	0.84
	11690	Tobermory	180.923	180.611	31.2	1.02
	11500	Collingwood	178.197	177.923	27.4	0.90
	11375	Parry Sound	183.122	182.797	32.5	1.07
	11195	Little Current	178.733	178.364	36.9	1.21
	11070	Thessalon	179.323	179.004	31.9	1.05
Lake Superior	10920	Gros Cap	185.964	185.655	30.9	1.01
	10750	Michipicoten	191.341	190.905	43.6	1.43
	10220	Rossport	205.652	205.133	51.9	1.70
	10050	Thunder Bay	185.374	184.893	48.1	1.58

Figs. 24-29 are only meant to present a general trend of the differences which may occur between IGLD 80 and IGLD 55. The adjustments presented in this study, however, do not contain any water-level transfer observations. These observations should reduce the height differences between MWL estimates at some stations pairs located on the same lake.

Looking at fig. 24, the first item to notice is that the IGLD 80 heights of Cape Vincent (station 2000) and Kingston (station 13988) are 14.8 cm (0.49 ft) and 14.1 cm (0.46 ft), respectively, higher than their published IGLD 55 heights. The relative height difference, however, between Cape Vincent and Olcott (station 2076) is only -2.6 cm (-0.09 ft). Once again, it should be noted that these results do not include water-level transfer observations. The addition of water-level transfer observations could decrease some of these differences. Although, in some cases, where the leveling data indicates that the water-level transfer observation should not have been used in 1955, these differences could be larger. This includes both primary and secondary stations in IGLD 55.

Fig. 25 gives the differences between preliminary IGLD 80 and published IGLD 55 on Lake Erie for stations Buffalo, Toledo, Port Colborne, and Kingsville. Notice that the absolute difference increased from Lake Ontario to Lake Erie, i.e., on Lake Ontario, station Olcott was 12.4 cm (0.41 ft), while on Lake Erie station Buffalo was 16.7 cm (0.55 ft). Once again, the relative difference between IGLD 80 and IGLD 55 on Lake Erie is small. The difference between IGLD 80 and IGLD 55 at stations Toledo and Buffalo is approximately the same, differing by only 1.3 cm (0.04 ft), and stations Kingsville and Toledo differ by only 1.8 cm (0.06 ft).

Lake St. Clair has two stations in the special network. The difference between IGLD 80 and IGLD 55 at station St. Clair Shores (station 4052) is 18.9 cm (0.62 ft) and at Belle River (station 11965), it is 19.8 cm (0.65 ft). (See fig. 26.)

The relative difference between preliminary IGLD 80 and published IGLD 55 on Lake Huron between DeTour (station 5099) and Lakeport (station 5002) is large, i.e., 8.1 cm (0.27 ft). The difference, however, between stations DeTour and Thessalon (station 11070) is only 3.2 cm (0.10 ft). (See fig. 27.) Once again, there appears to be an increase of almost 3 cm (0.1 ft) between Lake Erie and Lake Huron. That is, the difference between IGLD 80 and IGLD 55 at station Toledo on Lake Erie is 18.0 cm (0.59 ft) and it is 20.6 cm (0.68 ft) at station Harbor" Beach on Lake Huron.

A portion of the large relative difference between Harbor Beach and DeTour is due to the combined adjustment of U.S. and Canadian data.
For the IGLD 55 network, single-route leveling lines were used to connect the lakes, and water-level transfer observations were used to tie all the water-level stations together. Looking back at figs. 6 and 15, it can be seen that when the two networks were adjusted separately, there was a significant difference between adjusted MWL surfaces at DeTour and Thessalon (station 11070). When the two networks were combined, the adjusted MWL surfaces differed by only 2.2 kgal-cm (0.07 ft). This will cause a larger deviation from published IGLD 55. This is the main reason for using a network instead of single leveling lines

It should be noted again that the Canadian data contain magnetic error and that an average magnetic constant was used to compute the magnetic correction for the Canadian data. As previously stated, the Canadian Geodetic Survey Division is releveling a portion of the network in this area. The new leveling data will be substituted for the old leveling when it becomes available. A more detailed analysis of the magnetic error for some of the instruments used in this area can be performed at that time.

Fig. 28 gives the differences between preliminary IGLD 80 and published IGLD 55 on Lake Michigan for Calumet Harbor (station 7044) and Ludington (station 7023). The relative difference between stations is only -0.4 cm (-0.01 ft) and the absolute height differences are almost the same as Harbor Beach on Lake Huron, i.e., Ludington is 20.2 cm (0.66 ft), Calumet Harbor is 19.8 cm (0.65 ft), and Harbor Beach is 20.6 cm (0.68 ft).

The remaining Great Lake, Lake Superior, has a large difference between preliminary IGLD 80 and published IGLD 55. (See fig. 29.) The absolute height difference at Grand Marais (station 9090) is 45.7 cm (1.50 ft) and at Thunder Bay (station 10050), it is 48.1 cm (1.58 ft). There also are large relative differences between Grand Marais and Pt. Iroquois, i.e., 14.5 cm (0.48 ft), and Gros Cap and Thunder Bay, i.e., 17.2 cm (0.56 ft). This was expected because both the Canadian and U.S. leveling networks when adjusted separately indicated that the MWL surface on Lake Superior tilted downward toward the east by about 14 kgal-cm (0.46 ft). (Refer to fig. 17.) This emphasizes the important of using a leveling network to estimate the mean water level surfaces on the Great Lakes system.

NAVD 88 AND IGLD 80

North American Vertical Datum of 1988 - Background

Approximately 625,000 km of leveling have been added to the National Geodetic Reference System (NGRS) since the 1929 general adjustment that created the National Geodetic Vertical Datum of 1929 (NGVD 29).
In the intervening years, numerous discussions were held to determine the proper time for the inevitable new general adjustment. In the early 1970's, NGS conducted an extensive inventory of the vertical control network. The search identified thousands of bench marks that had been destroyed, due primarily to post-World War II highway construction, as well as other causes. Many existing bench marks were affected by crustal motion associated with earthquake activity, post-glacial rebound (uplift), and subsidence resulting from the withdrawal of underground liquids. Other problems (distortions in the network) were caused by forcing the 625,000 km of leveling to fit previously determined NGVD 29 height values.
Some observed changes, amounting to as much as 9 m, are discussed in previous reports (Zilkoski 1986, Zilkoski and Young 1985).

In order to perform the new general adjustment, NGS prepared a budget initiative for fiscal year 1977 to finance this project, a revision of which was later approved, and the adjustment project, called the North American Vertical Datum of 1988 (NAVD 88), formally began in October 1977. The NAVD 88 project, scheduled for completion in 1991, has dominated NGS' Vertical Network Branch (VNB) activities since approval and funding in 1977. Major NAVD 88 tasks are described in detail in previous reports (Zilkoski 1986, Zilkoski and Young 1985).

Helmert blocking consists of the partitioning of 1.3 million unknowns (approximately 600,000 permanently monumented bench marks and 700,000 temporary bench marks) and associated observations into manageable blocks and performing the equivalent of a simultaneous least squares adjustment of the entire data set. Helmert blocking began in a production mode in October 1989, with the new general final adjustment targeted for completion by September 1990.

An important feature of the NAVD 88 program is the releveling of much of the first-order NGS vertical control network in the United States. The dynamic nature of the network requires a framework of newly observed height differences to obtain realistic, contemporary height values from the readjustment. To accomplish this, NGS identified 81,500 km (50,600 miles) for releveling. Replacement of disturbed and destroyed monuments precedes the actual leveling. This effort also includes the establishment of stable "deep-rod" bench marks, which will provide reference points for future "traditional" and "satellite" leveling systems. Field leveling of the 81,500 km network is being accomplished to Federal Geodetic Control Committee (FGCC) first-order, class II specifications, using the "double-simultaneous" method (Whalen and Balazs 1976) and is scheduled for completion in 1990.

One Network For Both IGLD 80 and NAVD 88

Fig. 5, which was discussed in a previous section, depicts the U.S. primary vertical network used in the NAVD 88 Datum Definition Study (Zilkoski et al. 1989). The values shown on fig. 5 are the differences between a U.S. primary vertical control network and a Canadian primary vertical control network. The Canadian heights from the Atlantic Ocean to the west end of Lake Superior were obtained from the adjusted Canadian network discussed in this report. The Canadian heights west of Lake Superior were obtained using single-line leveling routes only. The NAVD 88 adjustment will include the IGLD 80 network discussed in this report, plus water-level transfer observations determined to represent zero geopotential differences. This network will provide the best estimate of potential numbers for vertical control in the Great Lakes region.

The datum of the International Great Lakes Datum of 1955 was determined by holding the elevation of local mean water level fixed at Point-au-Pere. If NAVD 88 is not distorted by fixing more than one elevation, then a constant can be applied to the NAVD 88 geopotential numbers to obtain geopotential numbers relative to local mean water level at Rimouski. This would help to eliminate confusion between the two datums. In addition, all leveling data in NGS' data base will be incorporated into NAVD 88 and will have a published geopotential number. This will include most published IGLD 55 bench marks.

CONCLUSION

This paper described the history of vertical datums used in the Great Lakes region and gave the progress to date by the National Geodetic Survey (NGS) in support of the new adjustment of the International Great Lakes Datum of 1980 (IGLD 80).

To assist in identifying and documenting the impact of IGLD 80, NGS compiled a primary vertical control network using the latest U.S. and Canadian data available. The control network started at the mouth of the St. Lawrence and included leveling lines which surrounded the Great Lakes. Analyses of this network were helpful in determining the effects of the datum constraint, magnitudes of height changes from the present International Great Lakes Datum of 1955 (IGLD 55), deficiencies in network design, and additional releveling requirements. The results of this special project were discussed.

A comparison of the U.S. network adjusted heights and the Canadian network adjusted heights showed good overall agreement. The difference between the adjusted heights estimated using independent leveling data from Ft. Kent, Maine, to the west end of Lake Superior is only 6.3 cm. Some larger differences exist at intermediate points between the two end points, but this is expected in vertical network adjustments. This shows the importance of using a leveling network instead of single-route leveling lines to estimate the heights of bench marks.

Analyses of the latest available leveling data indicate that each lake represents an equipotential surface to some degree. On each lake there are some water-level stations which appear to be too high or too low relative to the rest of the stations on that lake. Mean water levels estimated at Thunder Bay (station 10050) and Grand Marais (station 9090) differ by only 0.6 kgal-cm (0.02 ft), but the west and east ends of Lake Superior differ by 17.4 kgal-cm (0.57 ft), with the west end being higher than the east end.

The analyses performed in this report provide the information needed to select water-level station pairs to be used to generate zero geopotential difference observations. These observations should also be included in the NAVD 88 network. IGLD 80 should be the same as NAVD 88 except for a constant offset for the difference between local mean water level at Rimouski and the corresponding published NAVD 88 geopotential number at Rimouski. Geopotential numbers from NAVD 88 should be used for IGLD 80 because they will provide the best estimate of hydraulic head.

If secondary gauge data are placed in computer-readable form, they could also be included in NAVD 88. In addition, the final epoch of water-level gauge data must be selected, i.e., 1977-1983 or 1982-1988. These data must be computed and entered into NGS7 data base prior to March 1990. This will reduce the amount of work required by IGLD personnel after the final adjustment. NGS will publish NAVD 88 heights and geopotential numbers for all bench marks included in NAVD 88.

NGS will work with IGLD representatives to develop an IGLD 80 implementation plan. This plan should include topics such as: IGLD committee responsibilities to IGLD 80 users and IGLD 80 users/responsibilities to implement IGLD 80. Products and services affected by IGLD 80 must be identified and documented. These tasks should be started before NAVD 88 is completed, so there can be a smooth transition from IGLD 55 to IGLD 80.

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Captions for Figures

Figure 1.--Water-Level transfer (Lippincott 1985).

Figure 2.--Vertical control network used in the International Great Lakes Datum of 1955 (Lippincott 1985).

Figure 3.--Vertical control network used in the International Great Lakes Datum of 1980.

Figure 4.--U.S. vertical network adjusted heights minus Canadian vertical control network adjusted heights (orthometric height differences at common junction bench marks,units = cm).

Figure 5.--Differences between U.S. primary vertical control network adjusted orthometric heights and Canadian vertical control network adjusted orthometric heights (Zilkoski et al. 1989).

Figure 6.--Estimates of mean water level (MWL) obtained from separate least squares adjustments of the U.S. network and the Canadian network (Lake Ontario), units = kgal-m.

Figure 7.--Estimates of mean water level (MWL) obtained from separate least squares adjustments of the U.S. network and the Canadian network (Lake Erie), units = kgal-m.

Figure 8.--Estimates of mean water level (MWL) obtained from separate least squares adjustments of the U.S. network and the Canadian network (Lake St. Clair), units = kgal-m.

Figure 9.--Estimates of mean water level (MWL) obtained from separate least squares adjustments of the U.S. network and the Canadian network (Lake Huron), units = kgal-m.

Figure 10.--Estimates of mean water level (MWL) obtained from separate least squares adjustments of the U.S. network and the Canadian network (Lake Michigan), units = kgal-m.

Figure 11.--Estimates of mean water level (MWL) obtained from separate least squares adjustments of the U.S. network and the Canadian network (Lake Superior), units = kgal-m.

Figure 12.--Differences in estimates of mean water level at each water-level station relative to one station on Lake Ontario, units = kgal-cm.

Figure 13.--Differences in estimates of mean water level at each water-level station relative to one station on Lake Erie, units = kgal-cm.

Figure 14.--Differences in estimates of mean water level at each water-level station relative to one station on Lake St. Clair, units = kgal-cm.

Figure 15.--Differences in estimates of mean water level at each water-level station relative to one station on Lake Huron, units = kgal-cm.

Figure 16.--Differences in estimates of mean water level at each water-level station relative to one station on Lake Michigan, units = kgal-cm.

Figure 17.--Differences in estimates of mean water level at each water-level station relative to one station on Lake Superior, units = kgal-cm.

Figure 18.--Estimates of mean water level obtained from a least squares adjustment of the combined U.S.-Canadian network (Lake Ontario), units = kgal-m. (Datum point was Point-au-Pere = 3.434 kgal-m).

Figure 19.--Estimates of mean water level obtained from a least squares adjustment of the combined U.S.-Canadian network (Lake Erie), units = kgal-m. (Datum point was Point-au-Pere = 3.434 kgal-m).

Figure 20.--Estimates of mean water level obtained from a least squares adjustment of the combined U.S.-Canadian network (Lake St. Clair), units = kgal-m. (Datum point was Point-au-Pere = 3.434 kgal-m).

Figure 21.--Estimates of mean water level obtained from a least squares adjustment of the combined U.S.-Canadian network (Lake Huron), units = kgal-m. (Datum point was Point-au-Pere = 3.434 kgal-m).

Figure 22.--Estimates of mean water level obtained from a least squares adjustment of the combined U.S.-Canadian network (Lake Michigan), units = kgal-m. (Datum point was Point-au-Pere = 3.434 kgal-m).

Figure 23.--Estimates of mean water level obtained from a least squares adjustment of the combined U.S.-Canadian network (Lake Superior), units = kgal-m. (Datum point was Point-au-Pere = 3.434 kgal-m).

Figure 24.--Differences in dynamic heights between preliminary IGLD 80 and published IGLD 55 on Lake Ontario.

Figure 25.--Differences in dynamic heights between preliminary IGLD 80 and published IGLD 55 on Lake Erie.

Figure 26.--Differences in dynamic heights between preliminary IGLD 80 and published IGLD 55 on Lake St. Clair.

Figure 27.--Differences in dynamic heights between preliminary IGLD 80 and published IGLD 55 on Lake Huron.

Figure 28.--Differences in dynamic heights between preliminary IGLD 80 and published IGLD 55 on Lake Michigan.

Figure 29.--Differences in dynamic heights between preliminary IGLD 80 and published IGLD 55 on Lake Superior.

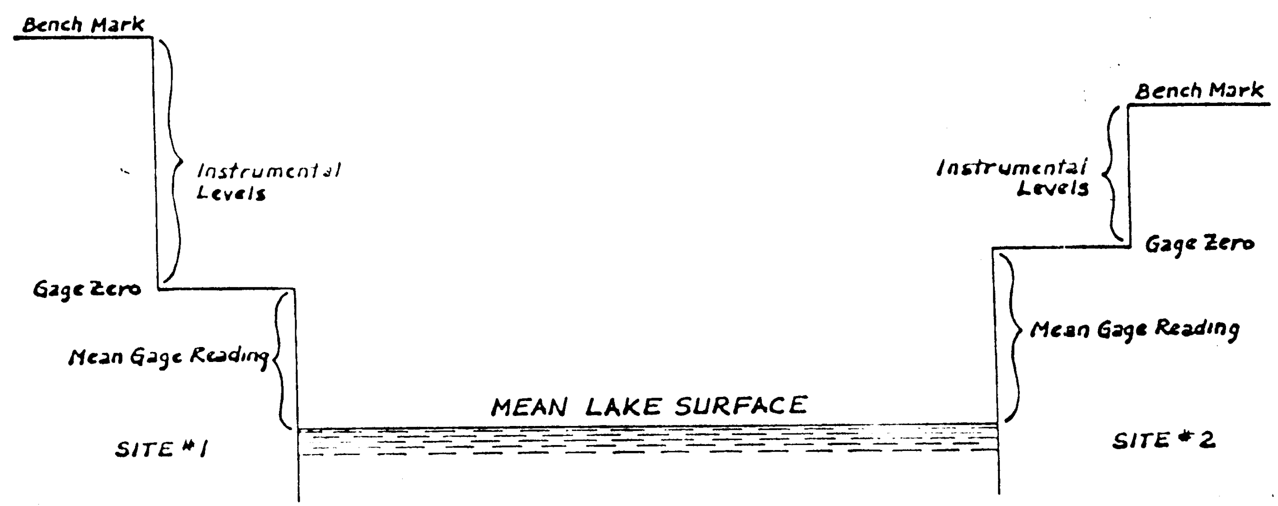


Figure 1 : WATER LEVEL TRANSFER ([illegible] 1985).

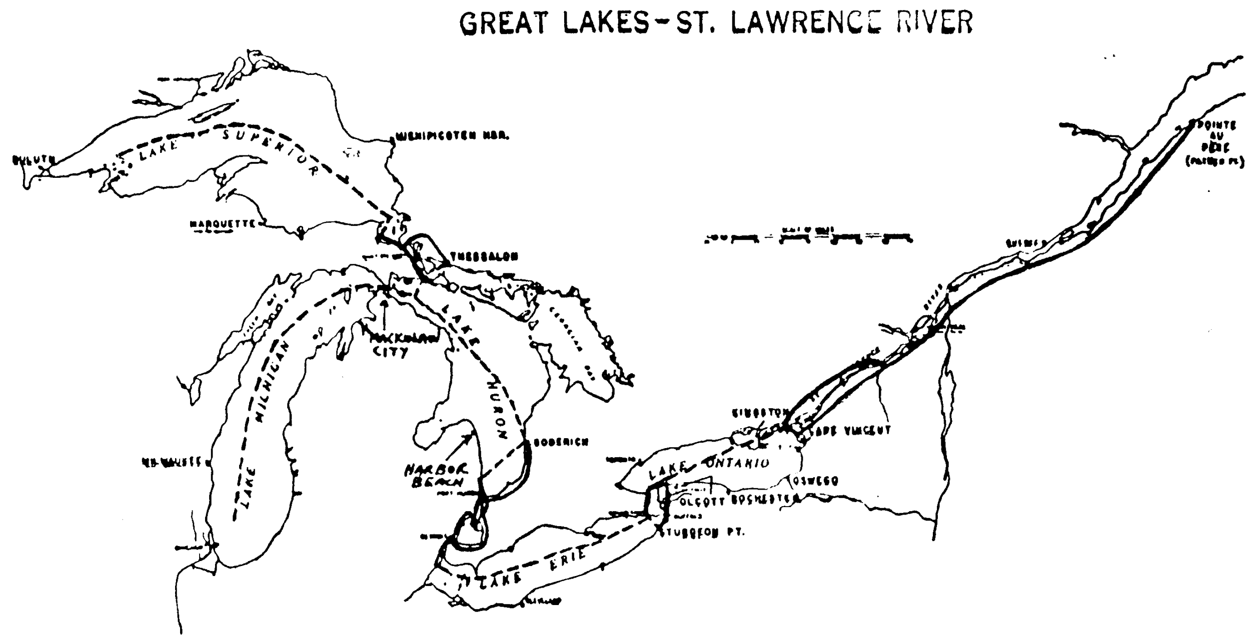


Figure 2 : LEVEL NETWORK, INTERNATIONAL GREAT LAKES DATUM (Lippincott 1985).

IGLD 80 VERTICAL CONTROL NETWORK

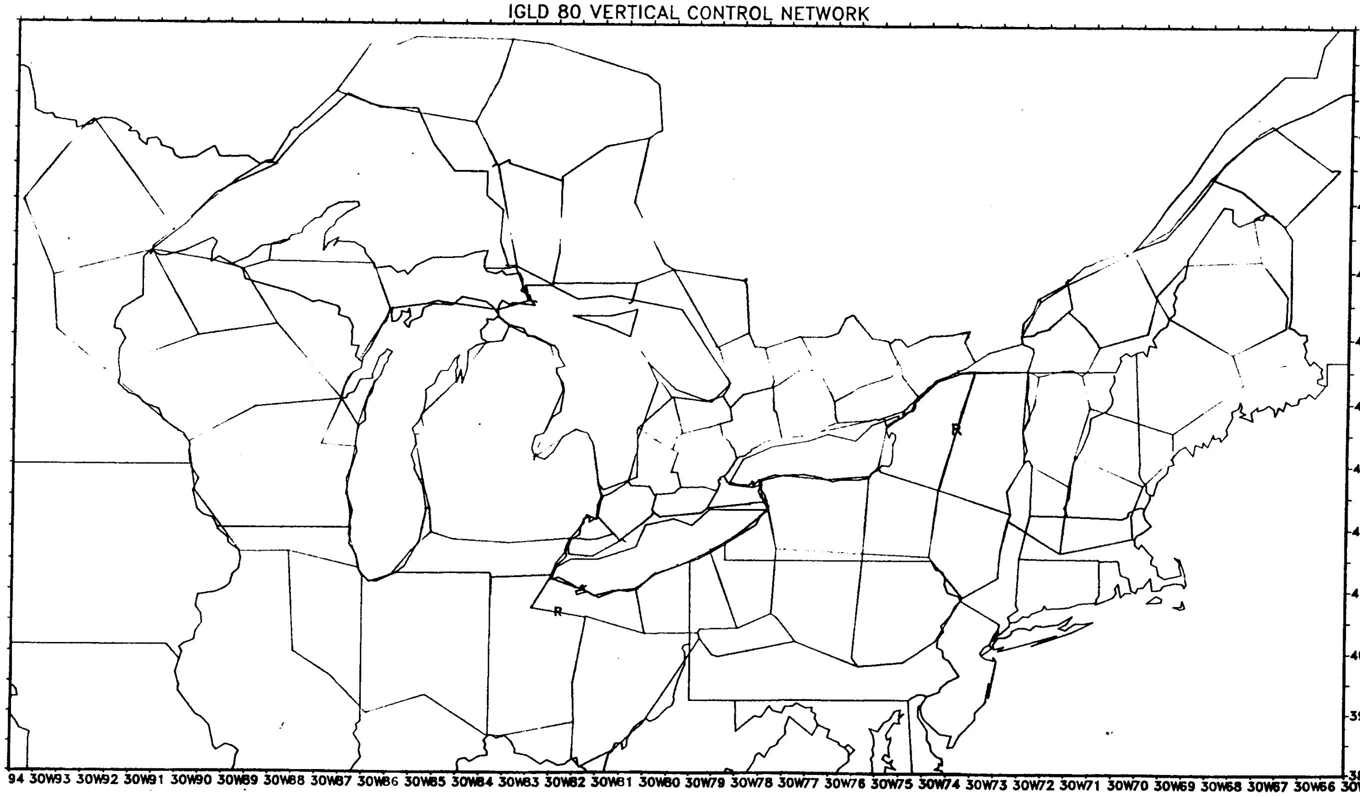
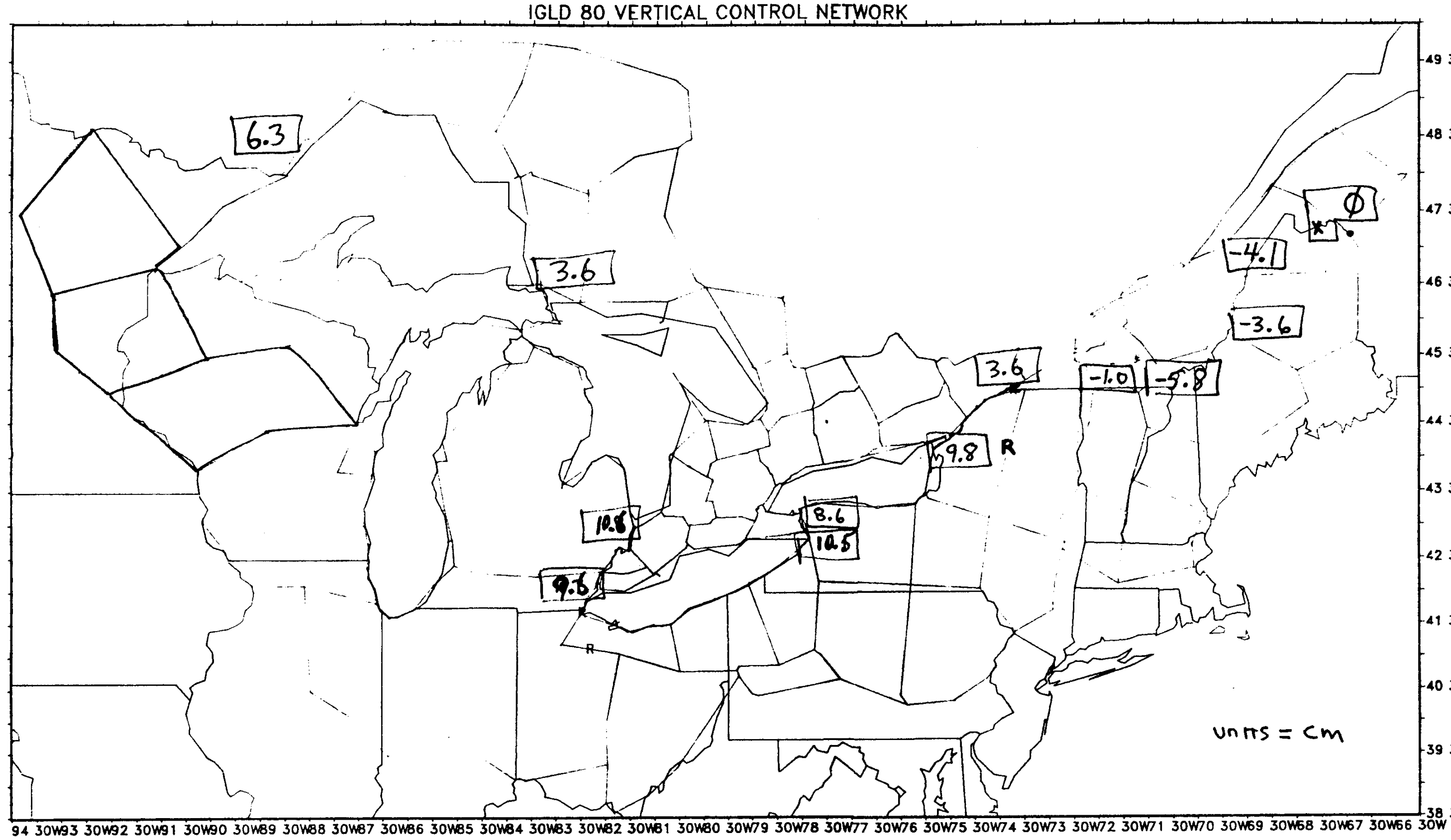


Figure 3. Canadian and U.S. Vertical Network used in the IGLD 80 adjustment study.

IGLD 80 VERTICAL CONTROL NETWORK



(4) U.S. Vertical Network Adjusted Heights minus Canadian Vertical Network Adjusted Heights (Orthometric Heights, UNITS = Cm)

Differences at common juction bench marks

3cm ≈ 0.1'

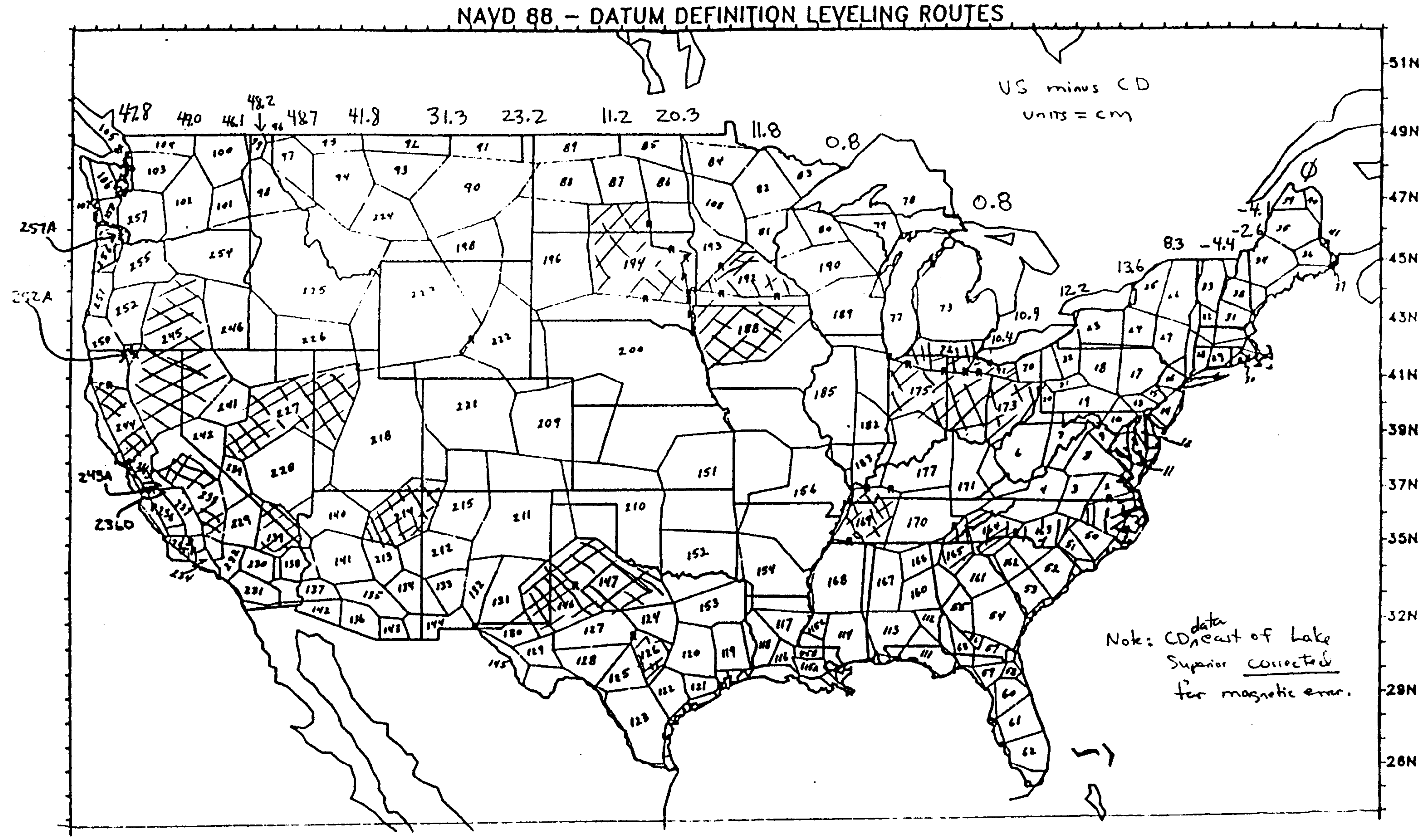
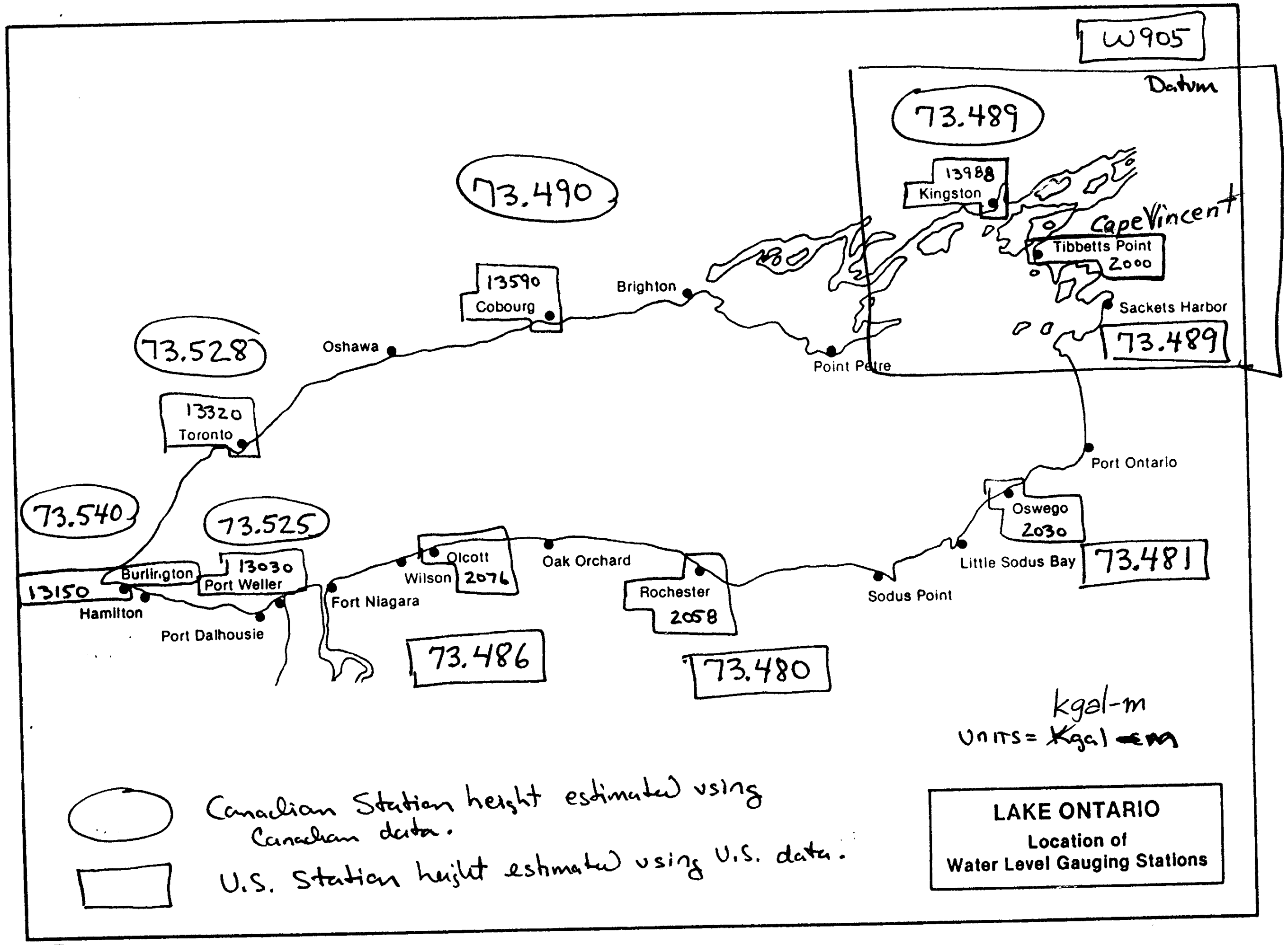


Fig. 5 Differences between ~~adjusted heights~~ ~~estimated~~ U.S. primary vertical control network, adjusted orthometric height and Canadian primary vertical control network adjusted heights.
(Zilkoski et al. 1989).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Cape Vincent
Tibbetts Point
2000
Sackets Harbor
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73.490
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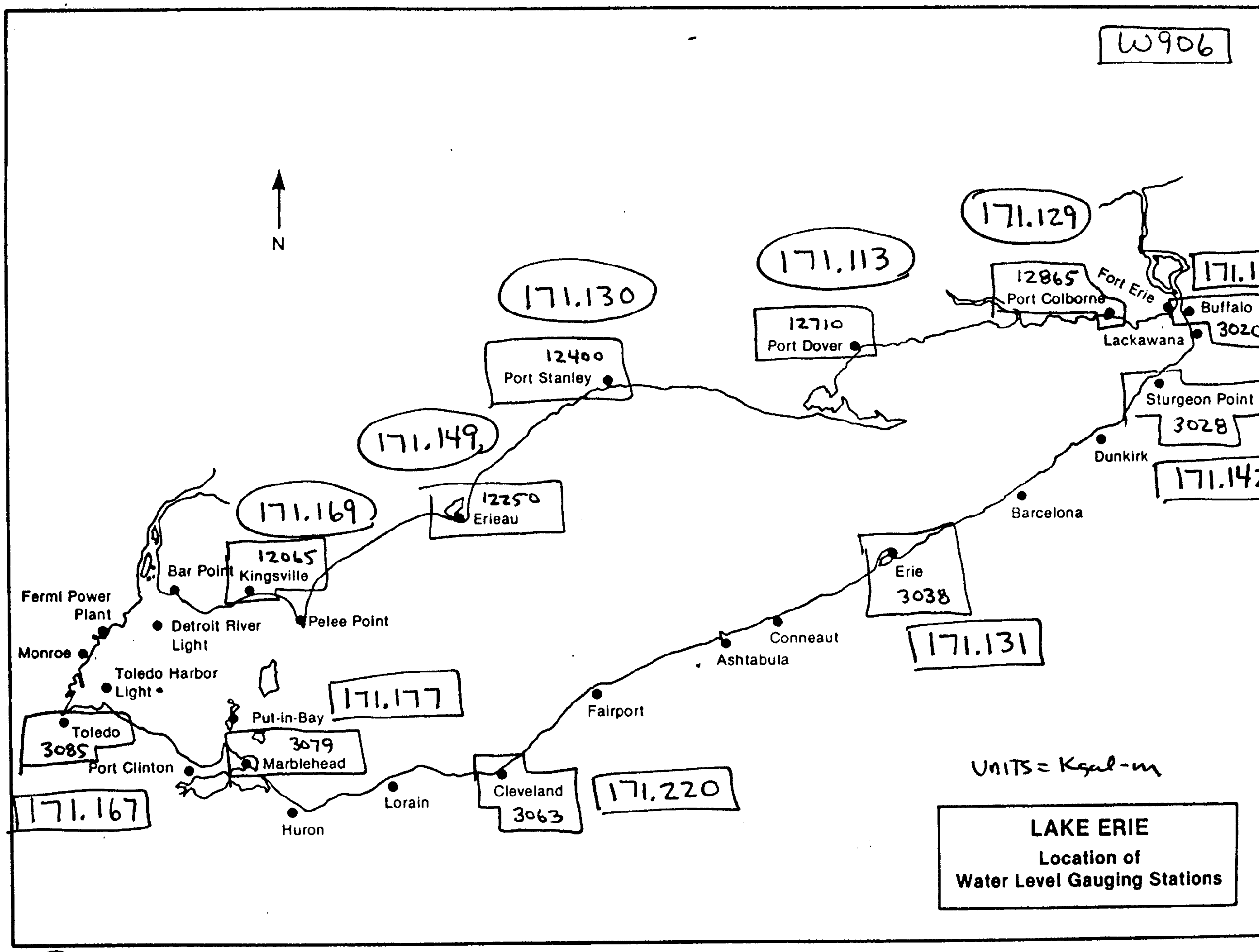
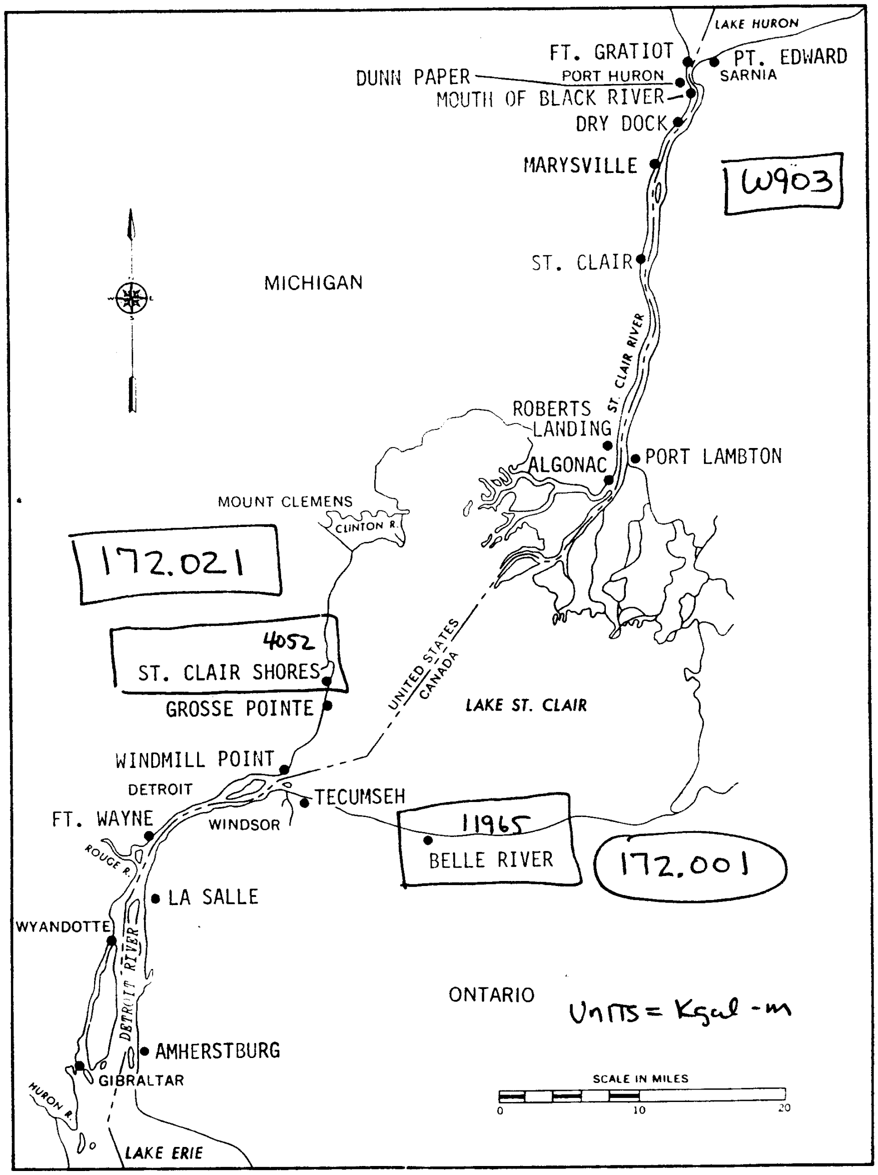
Cobourg
Brighton
Point Petre
73.528
Oshawa
13320
Toronto
Port Ontario
73.540
73.525
13030
Port Weller
Burlington
13150
Hamilton
Port Dalhousie
Fort Niagara
Wilson
Olcott
2076
Oak Orchard
Rochester
2058
Sodus Point
Little Sodus Bay
Oswego
2030
73.481
73.486
73.480
kgal-m
UNITS = ~~Kgal~~ ~~cm~~
Canadian Station height estimated using Canadian data.
U.S. Station height estimated using U.S. data.
LAKE ONTARIO
Location of
Water Level Gauging Stations

6



LAKE ERIE
Location of Water Level Gauging Stations

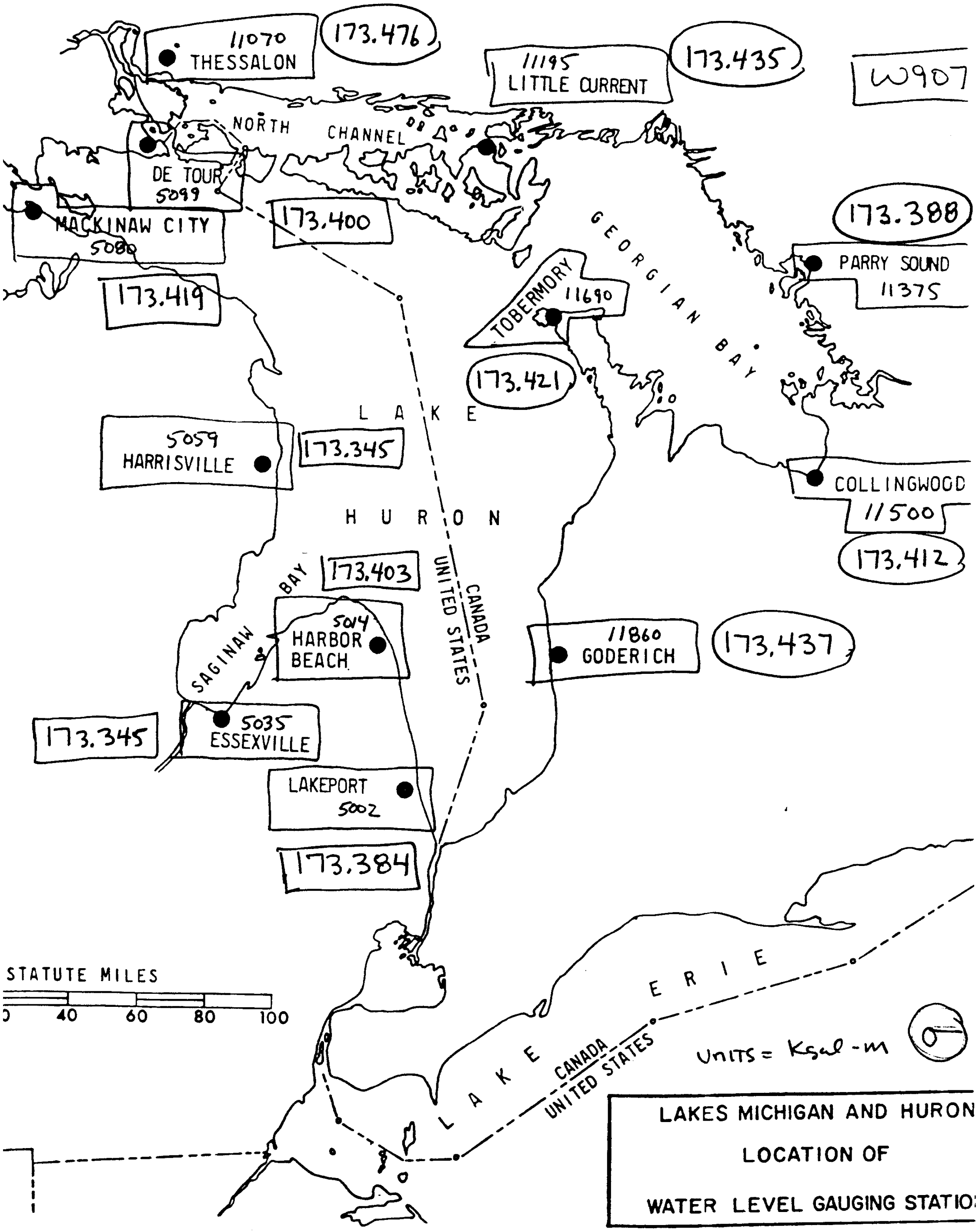
7



ST. CLAIR - DETROIT RIVERS
LOCATION OF
WATER LEVEL GAUGING STATIONS

8

PLATE 3

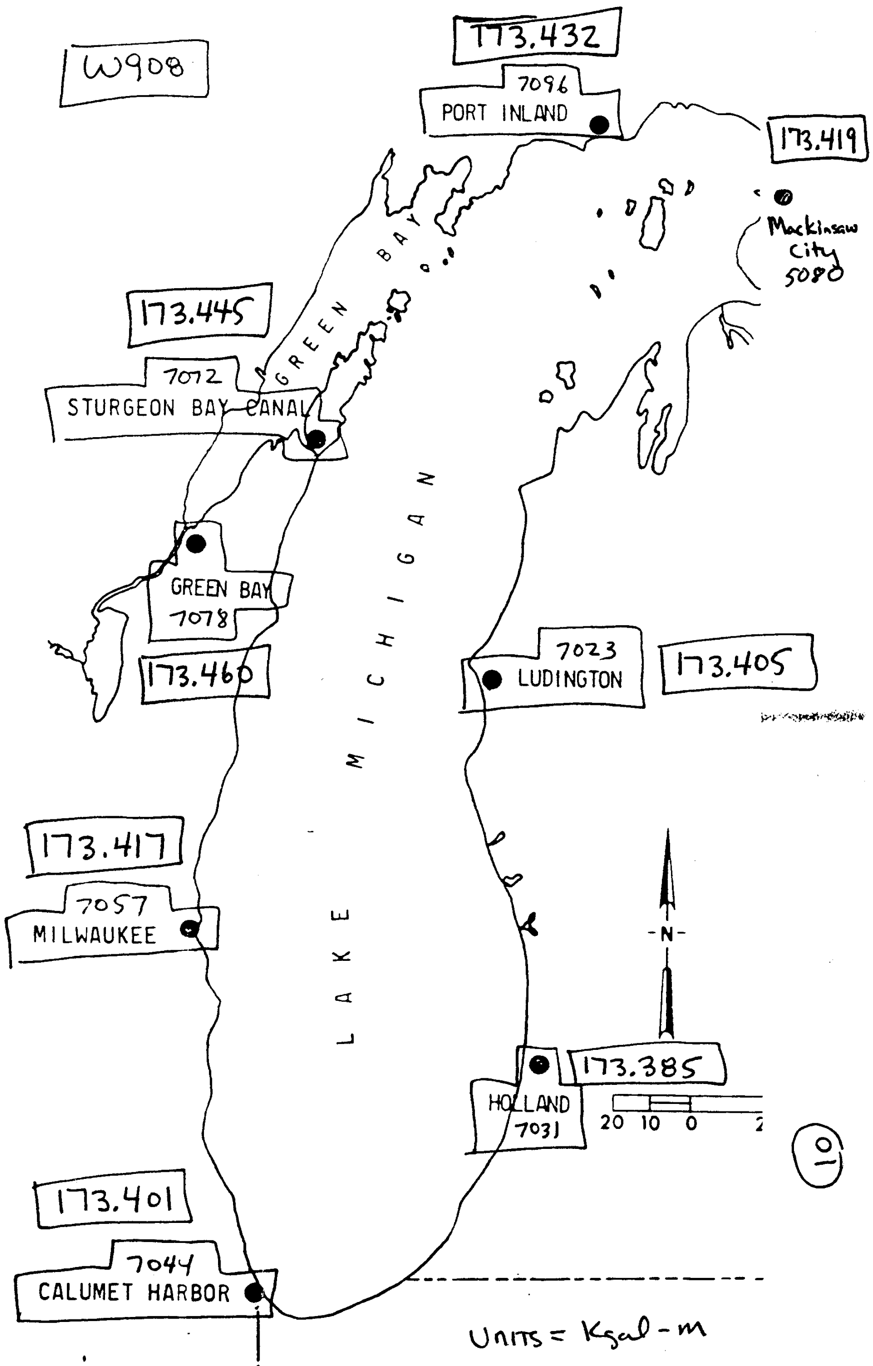


LAKES MICHIGAN AND HURON

LOCATION OF

WATER LEVEL GAUGING STATIO

PLA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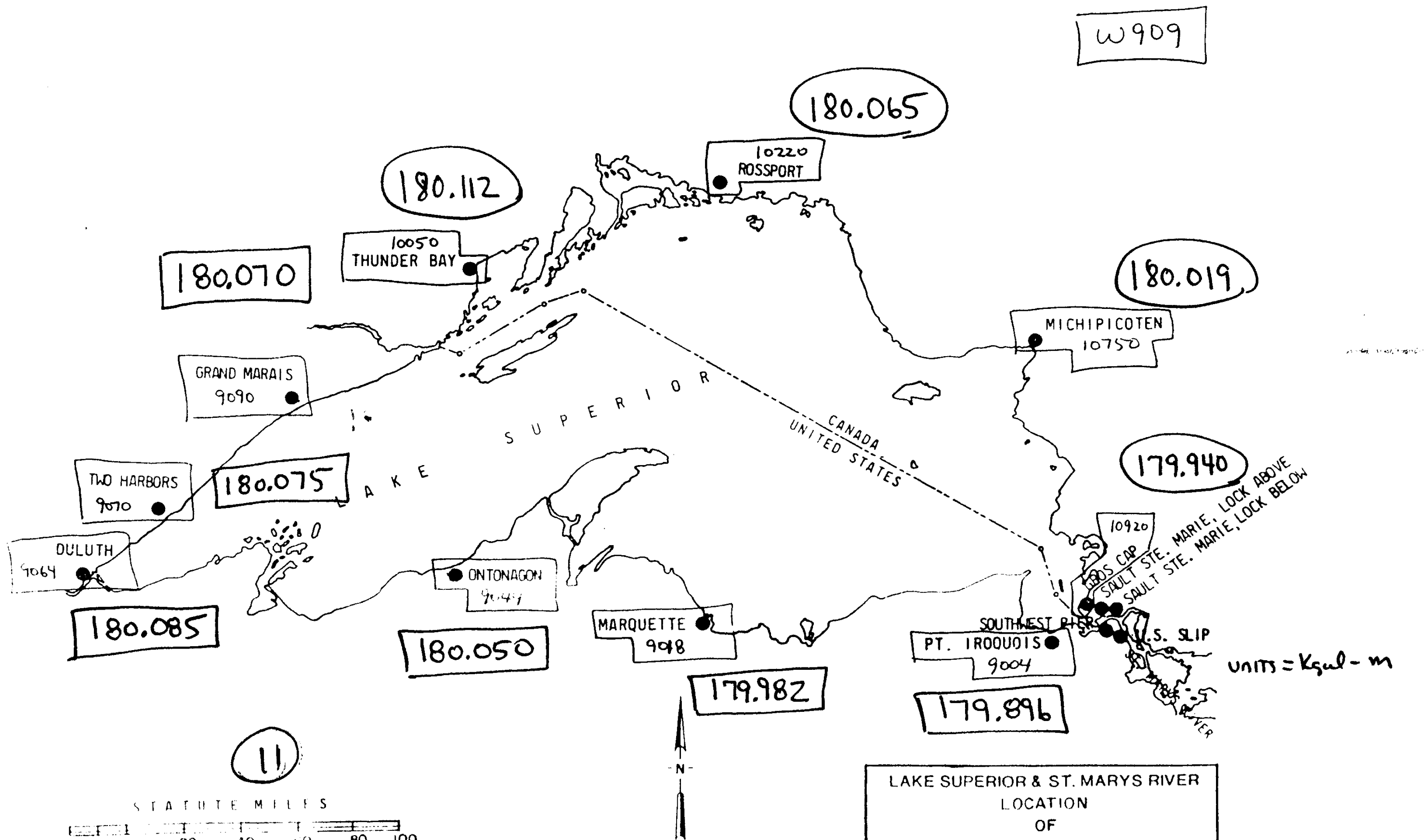
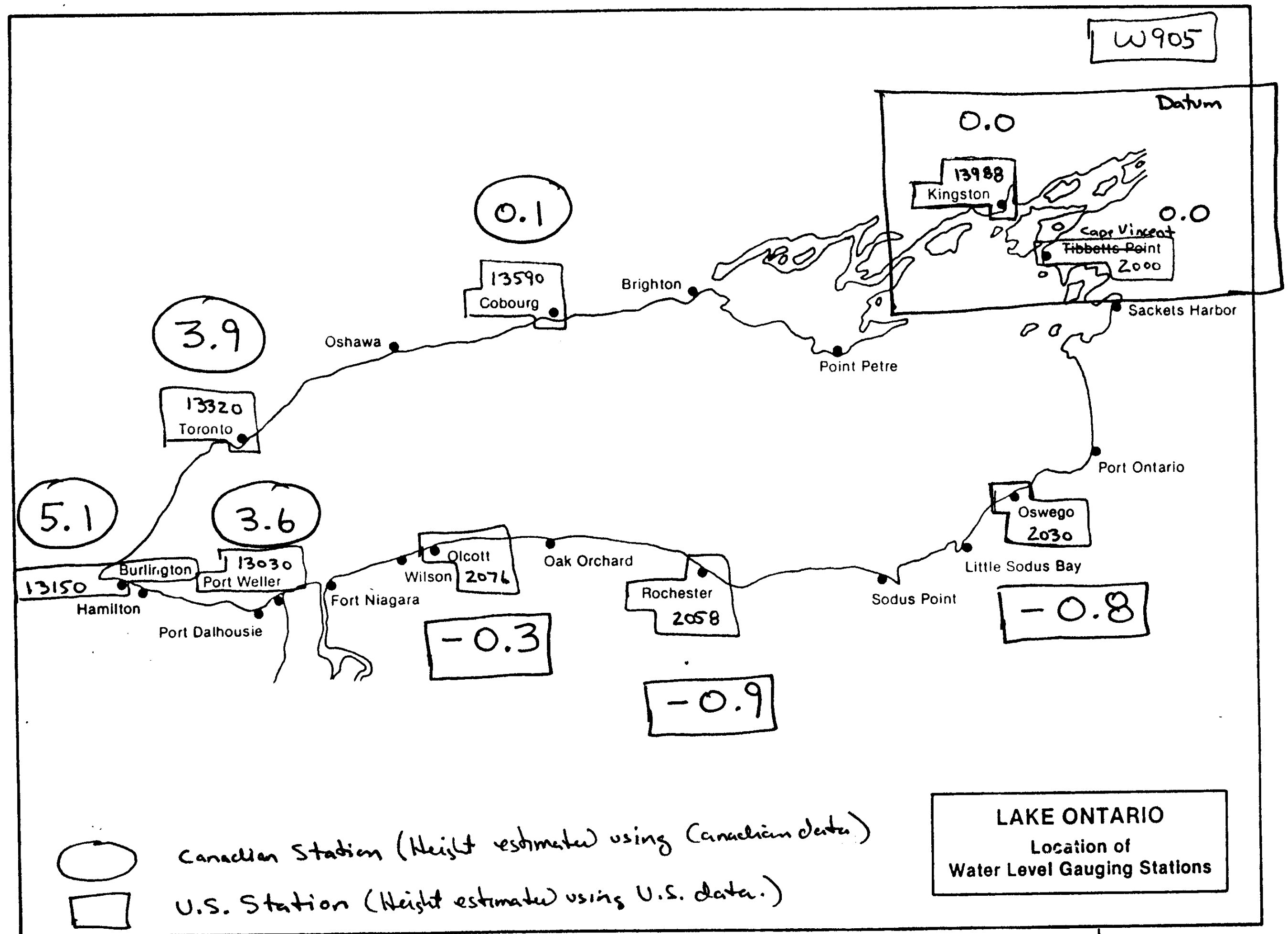
7096
PORT INLAND
173.419
Mackinsaw City
5080
173.445
7072
STURGEON BAY CANAL
GREEN BAY
GREEN BAY
7078
173.460
7023
LUDINGTON
173.405
LAKE MICHIGAN
173.417
7057
MILWAUKEE
N
173.385
HOLLAND
7031
20 10 0
173.401
7044
CALUMET HARBOR
Units = Kgal-m
10



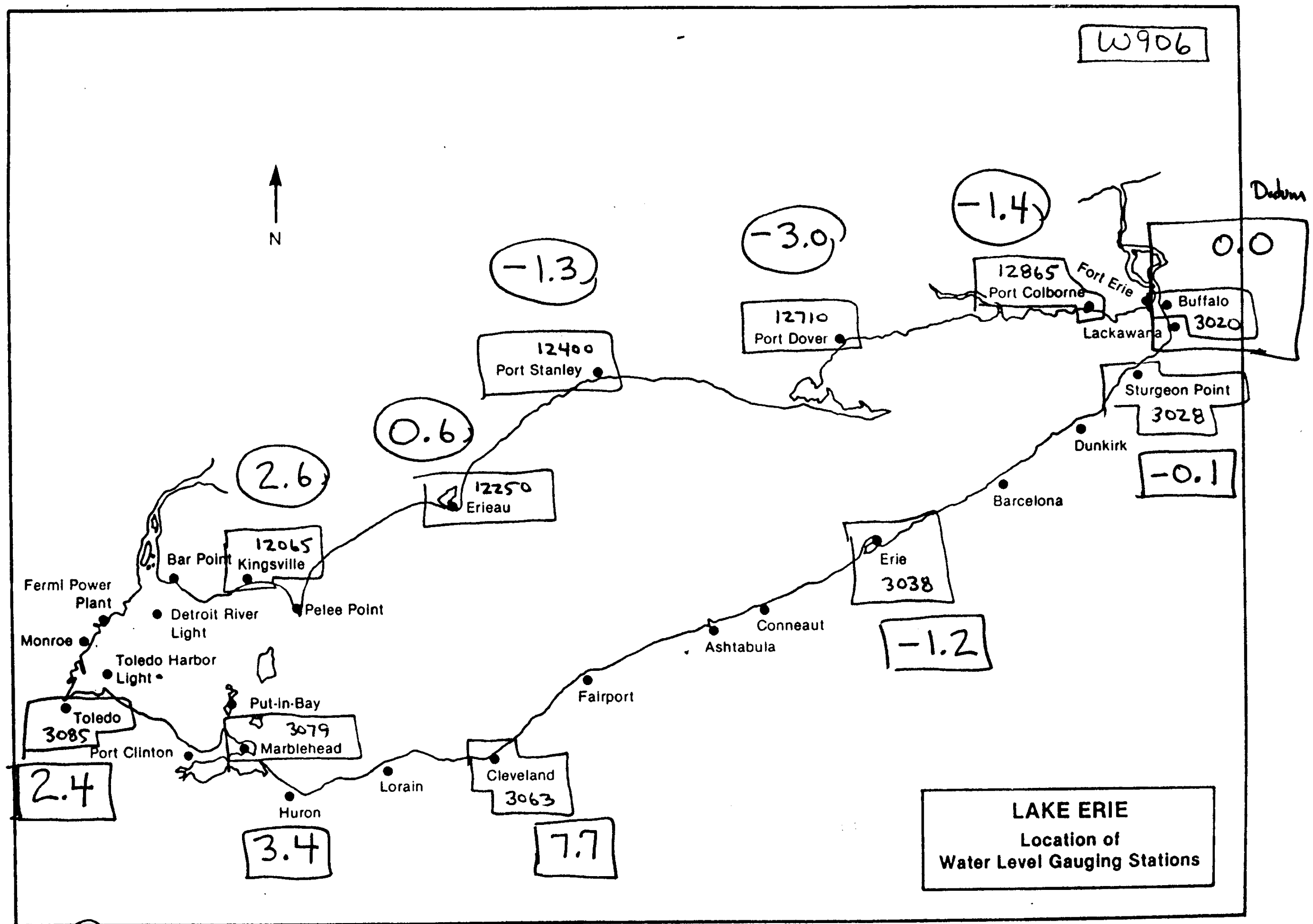
LAKE SUPERIOR & ST. MARYS RIVER
LOCATION
OF
WATER LEVEL GAUGING STATIONS

PLATE 1



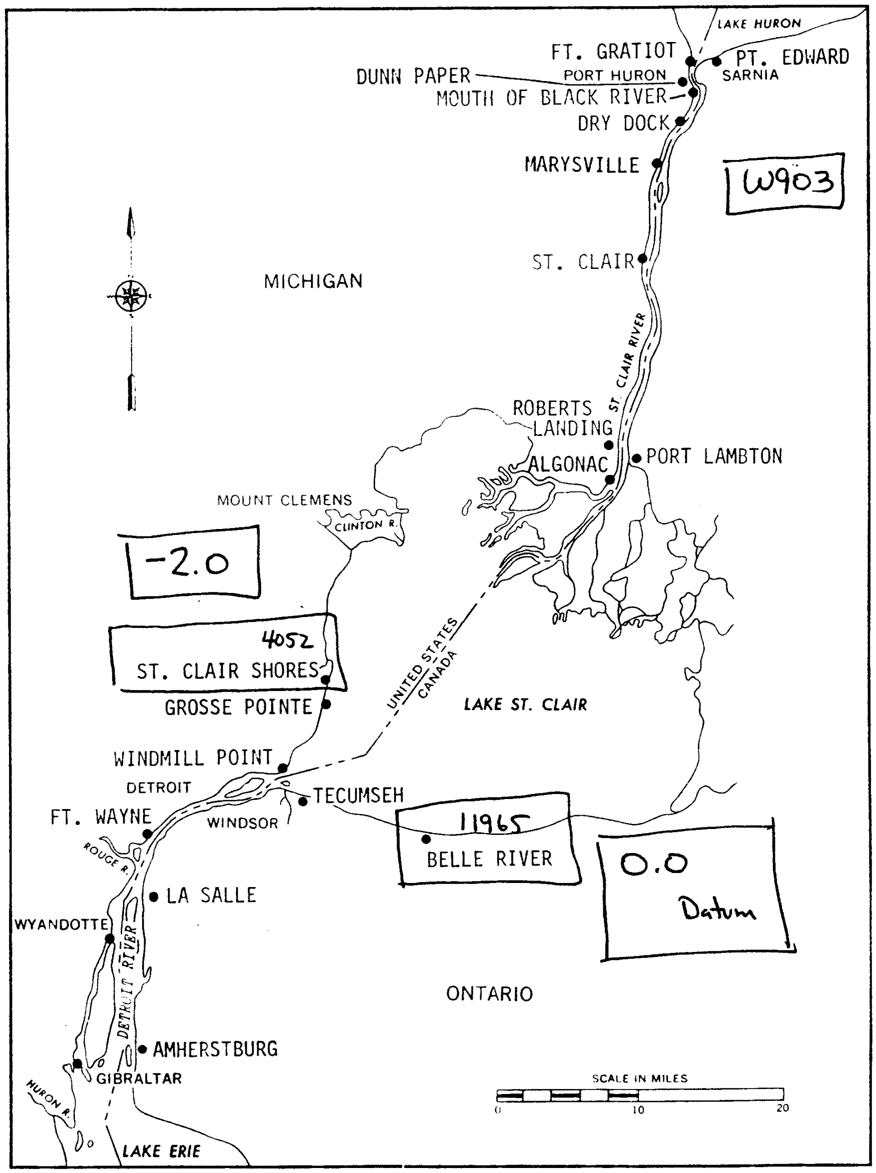
(12)

UNITS = ~~K~~gal-cm
≈ cm
3cm ≈ 0.1 ft



(13)

Units = Kgal cm

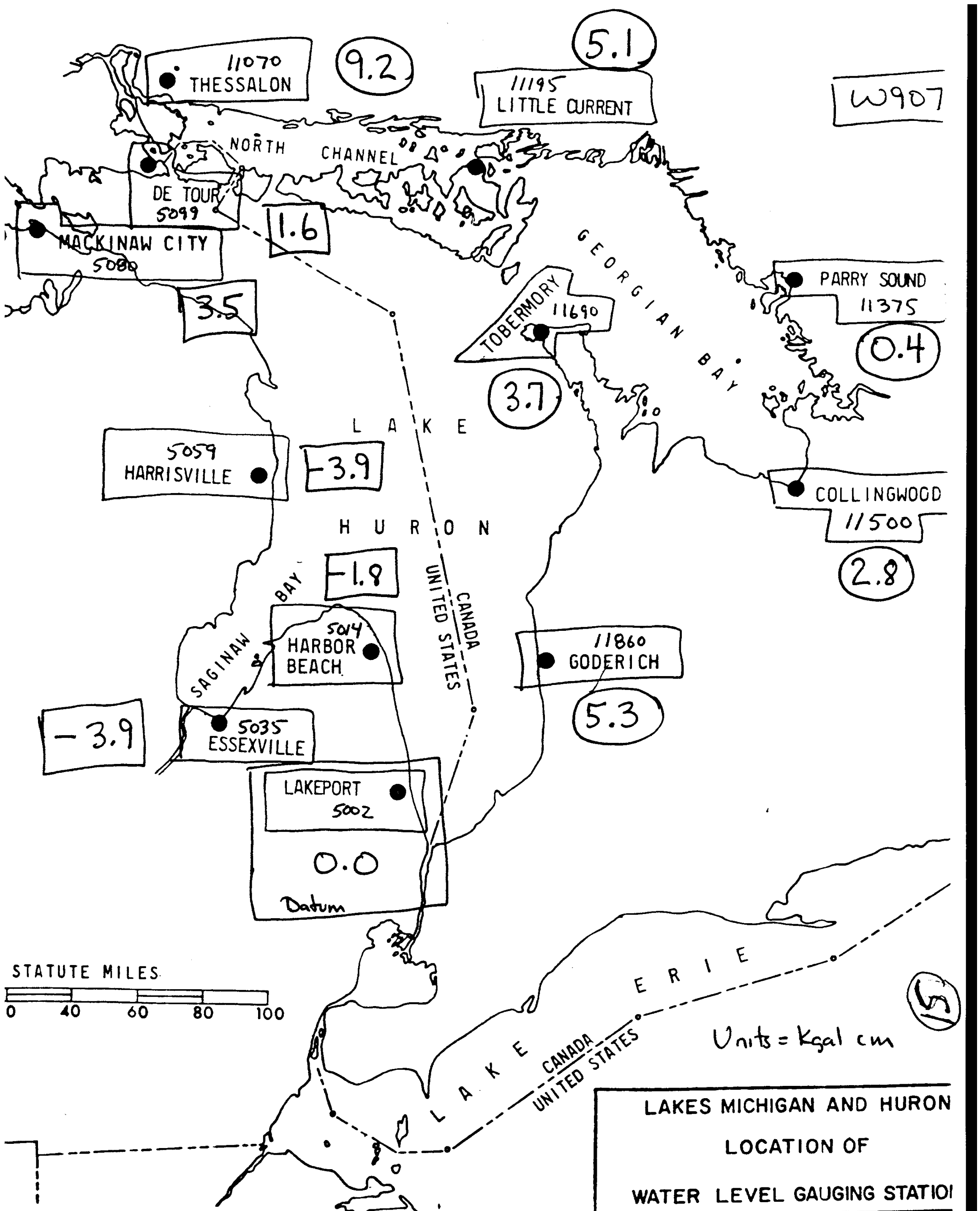


ST. CLAIR - DETROIT RIVERS
LOCATION OF
WATER LEVEL GAUGING STATIONS

Units = Kgsl cm

14

PLATE 3

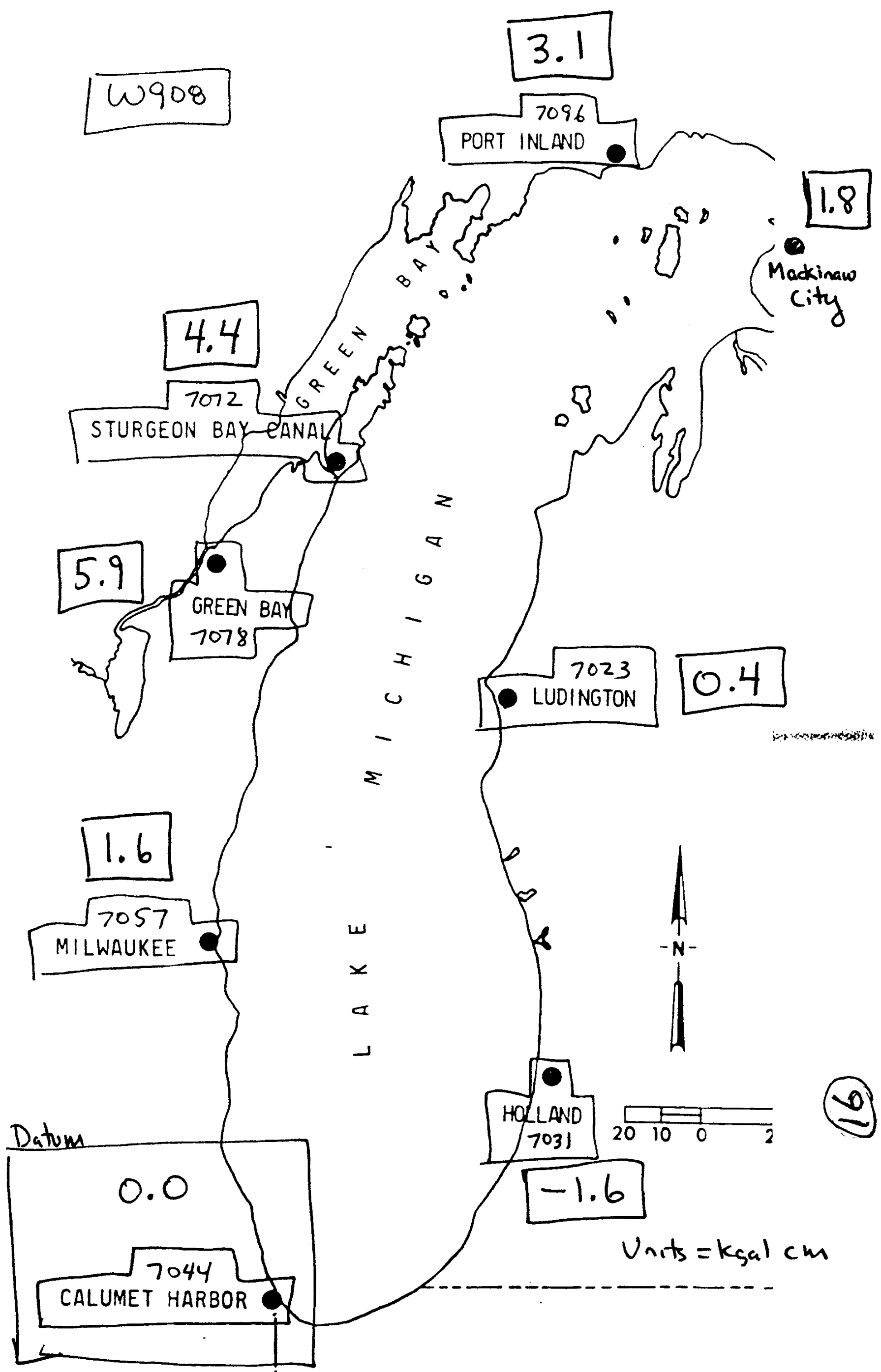


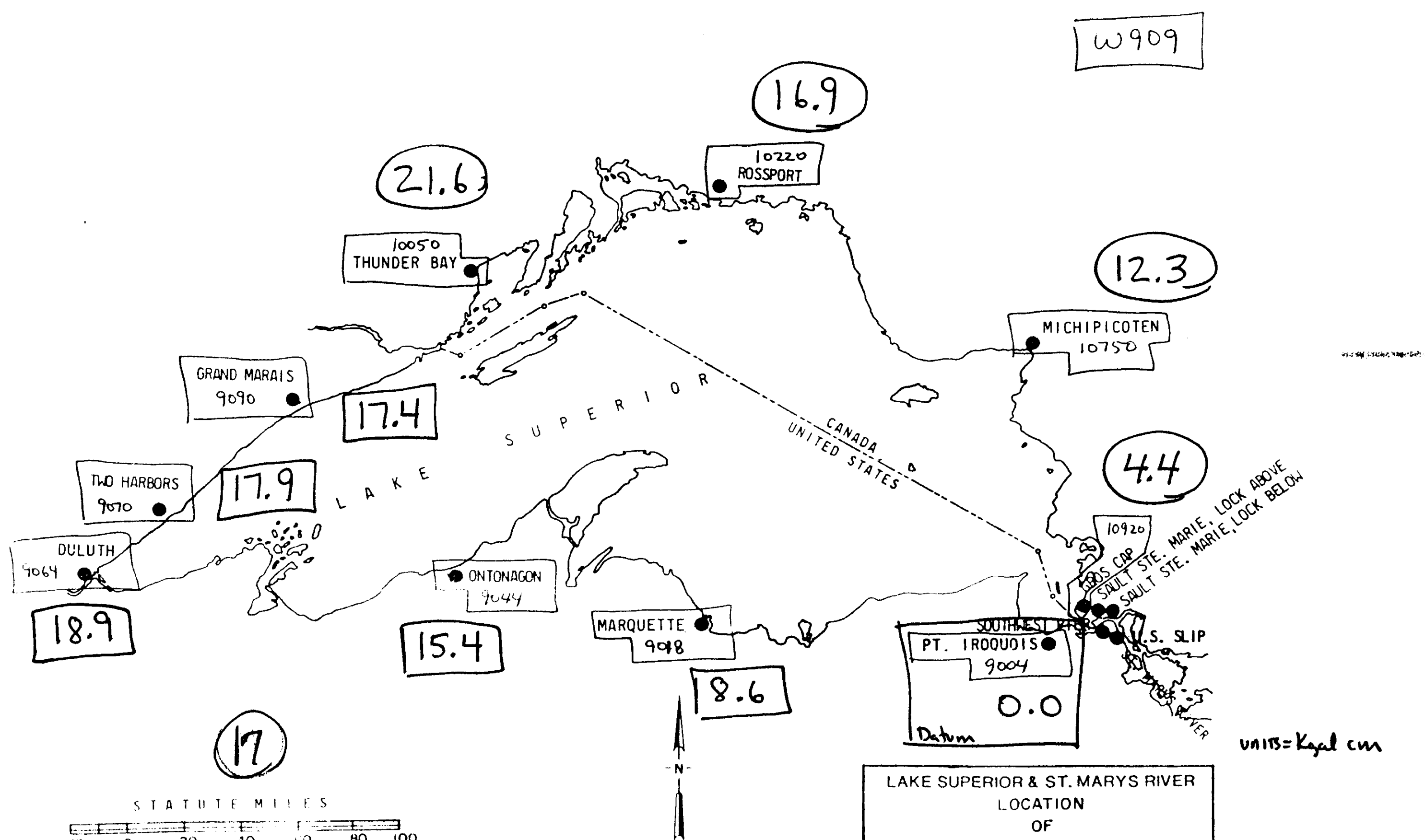
LAKES MICHIGAN AND HURON

LOCATION OF

WATER LEVEL GAUGING STATIOI

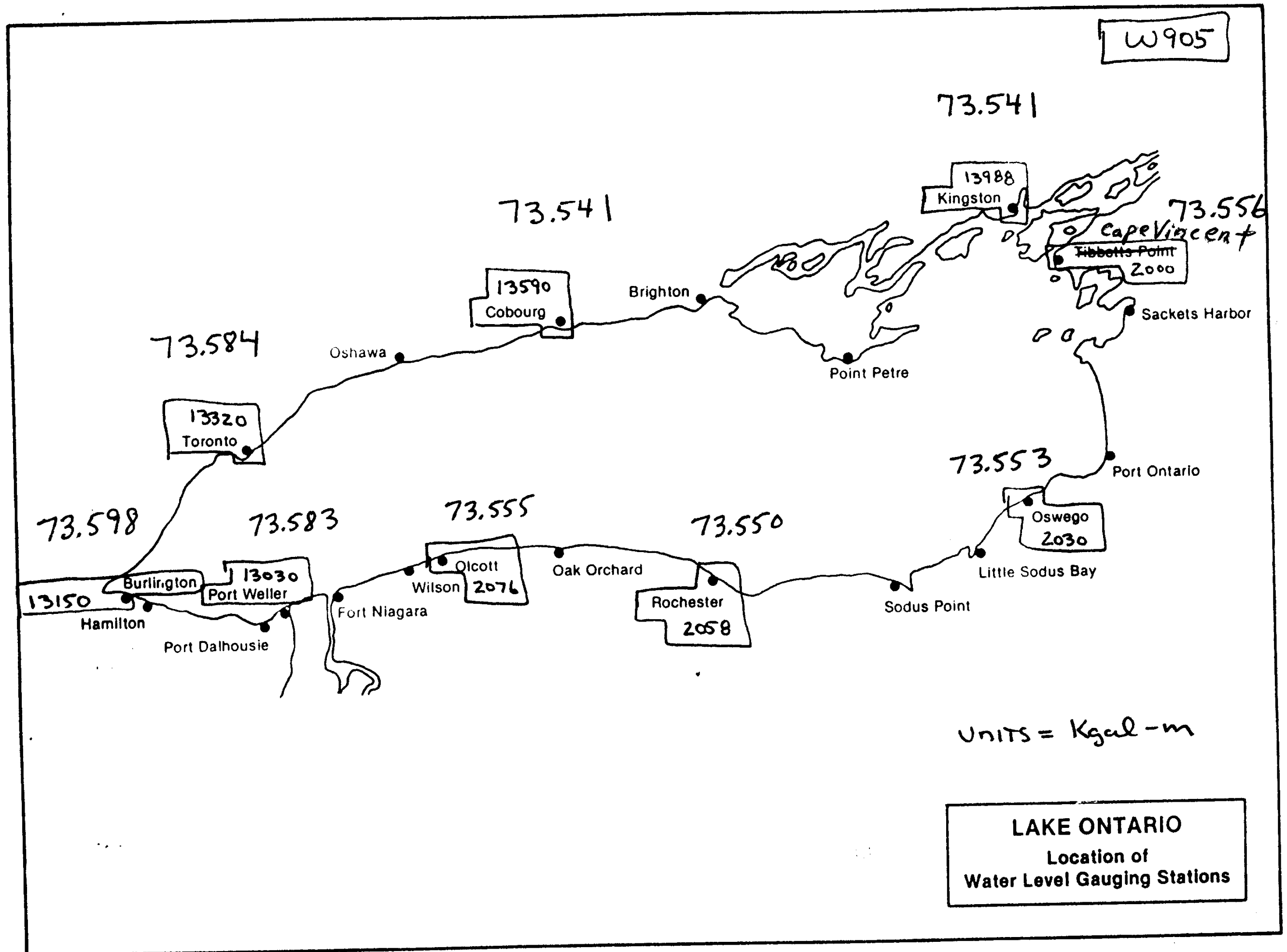
PLA

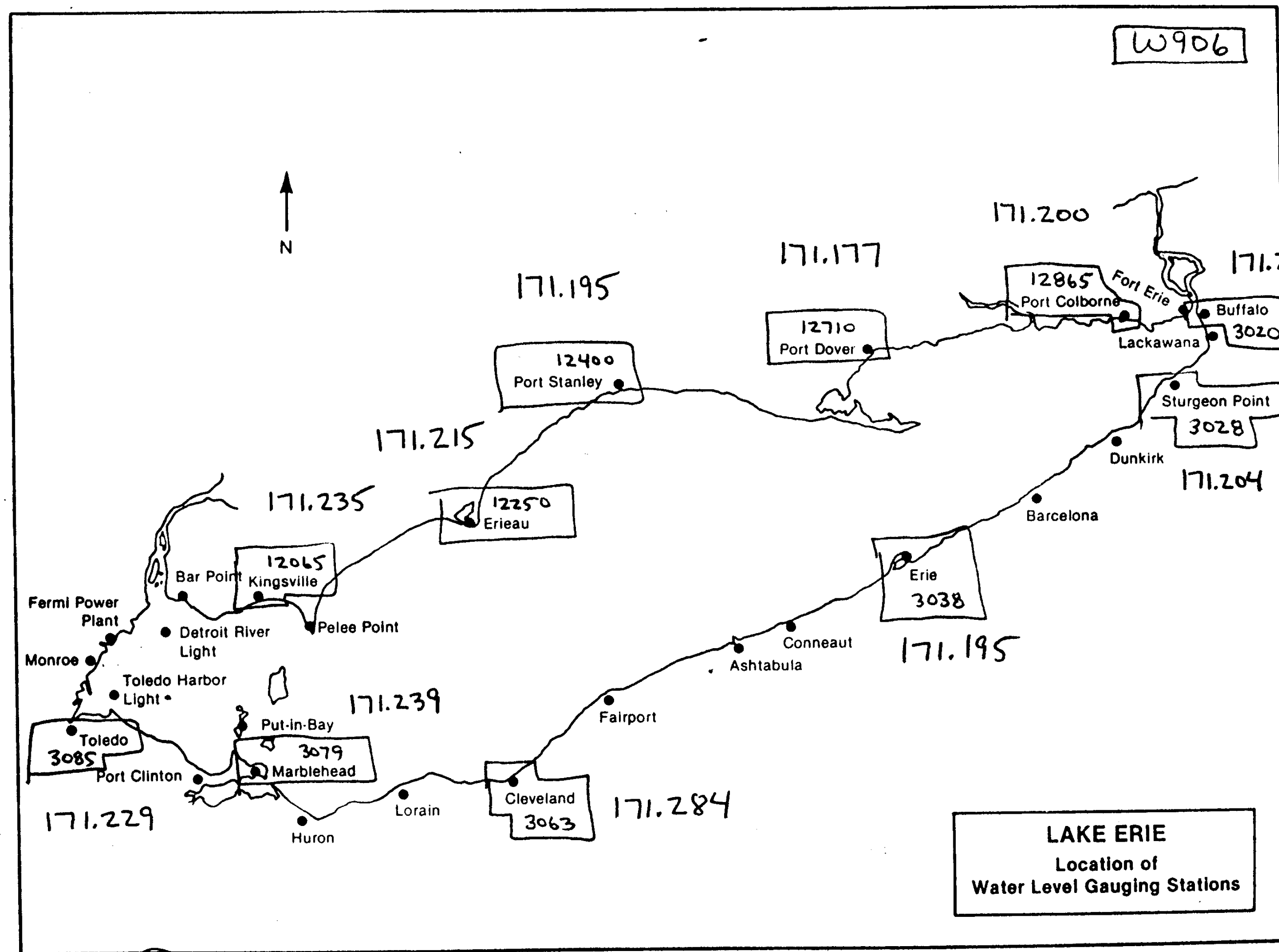

W908
3.1
7096
PORT INLAND
1.8
Mackinaw City
GREEN BAY
4.4
7072
STURGEON BAY CANAL
5.9
GREEN BAY
7078
LAKE MICHIGAN
7023
LUDINGTON
0.4
1.6
7057
MILWAUKEE
-N-
HOLLAND
7031
20 10 0
-1.6
Datum
0.0
7044
CALUMET HARBOR
Units = kgal cm
16

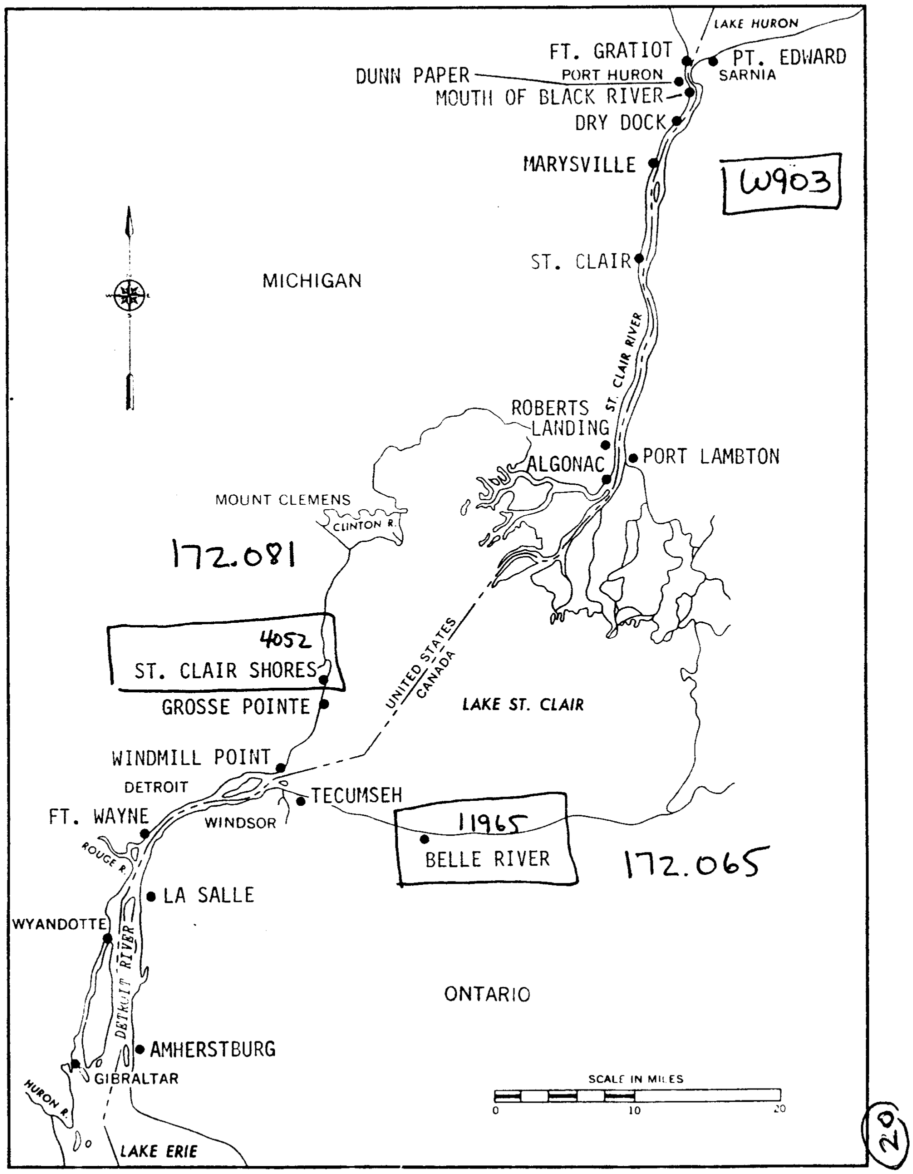


LAKE SUPERIOR & ST. MARYS RIVER
LOCATION
OF
WATER LEVEL GAUGING STATIONS

PLATE 1


W905
73.541
73.541
73.556
Cape Vincent
~~Tibbetts Point~~
2000
13988
Kingston
13590
Cobourg
Brighton
Sackets Harbor
Point Petre
73.584
Oshawa
13320
Toronto
73.553
Port Ontario
73.598
73.583
73.555
73.550
Oswego
2030
13150
Burlington
13030
Port Weller
Olcott
Wilson
2076
Oak Orchard
Rochester
2058
Little Sodus Bay
Sodus Point
Hamilton
Port Dalhousie
Fort Niagara
UNITS = Kgal-m
LAKE ONTARIO
Location of
Water Level Gauging Stations

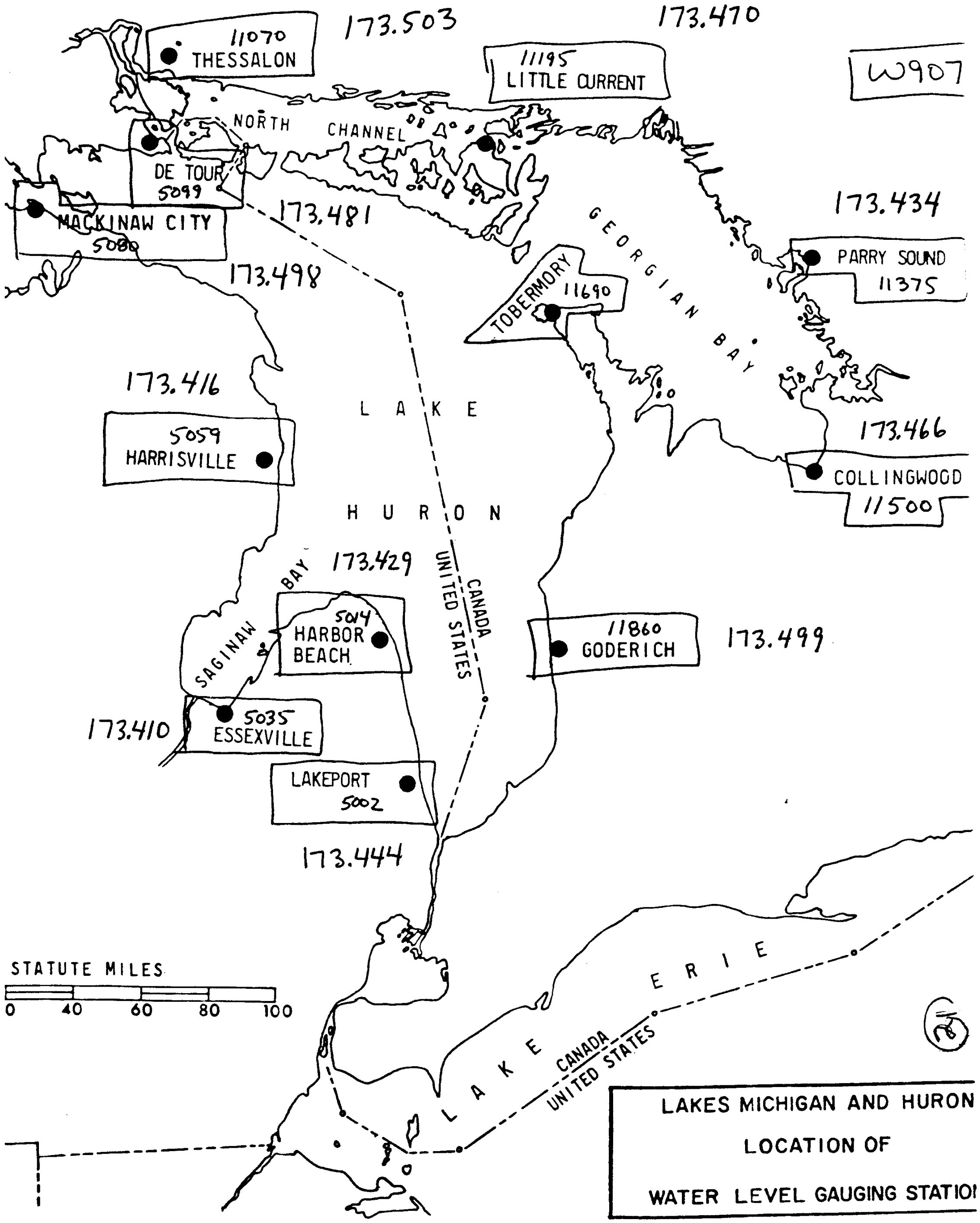

W906
N
171.200
171.177
171.195
171.205
12865
Port Colborne
Fort Erie
Buffalo
3020
Lackawana
12710
Port Dover
12400
Port Stanley
Sturgeon Point
3028
Dunkirk
171.204
171.215
171.235
12250
Erieau
Barcelona
12065
Kingsville
Bar Point
Erie
3038
Fermi Power
Plant
Detroit River
Light
Pelee Point
Conneaut
171.195
Monroe
Ashtabula
Toledo Harbor
Light
171.239
Fairport
Put-in-Bay
Toledo
3085
3079
Marblehead
Port Clinton
Cleveland
3063
171.284
171.229
Lorain
Huron
LAKE ERIE
Location of
Water Level Gauging Stations



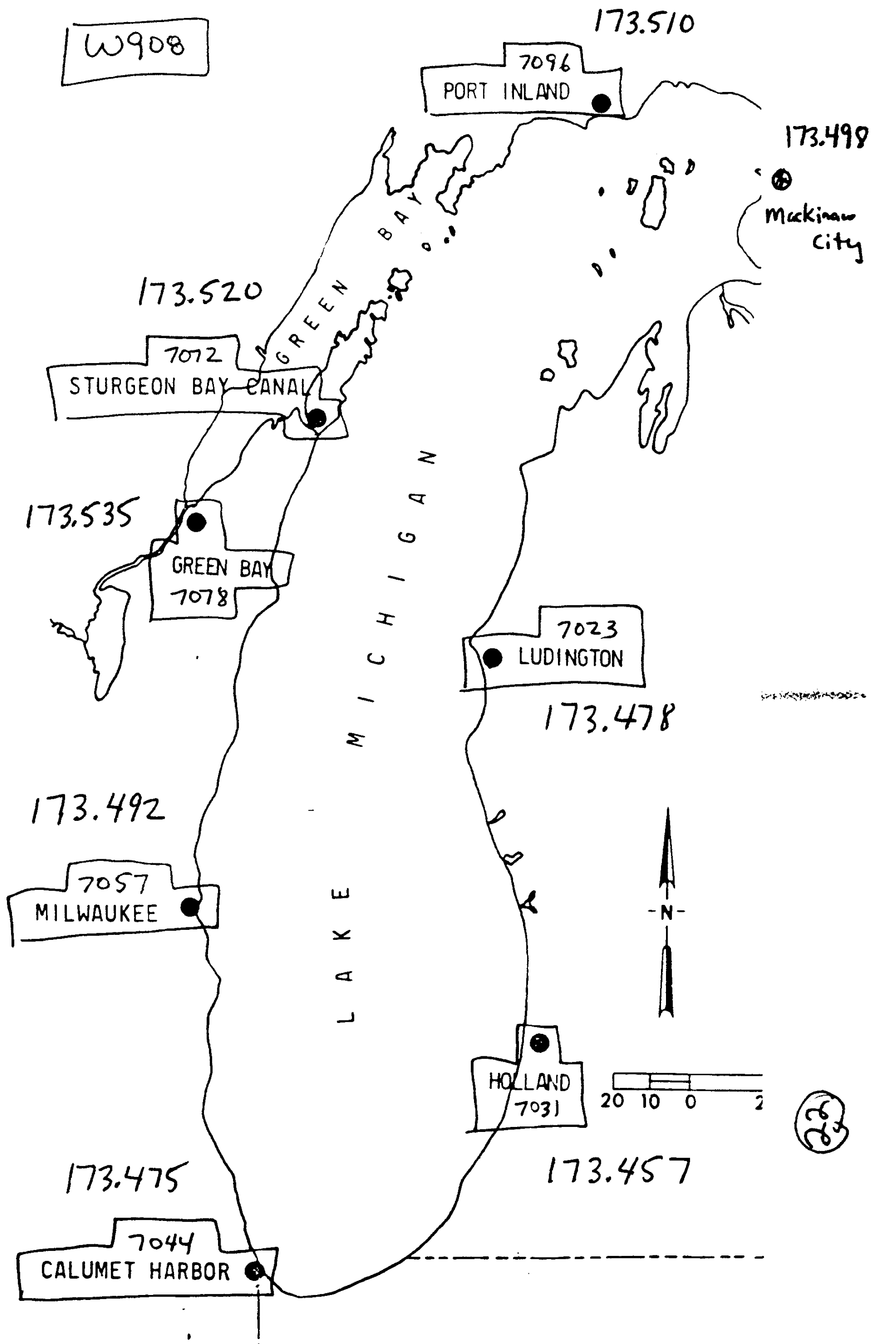
ST. CLAIR - DETROIT RIVERS
LOCATION OF
WATER LEVEL GAUGING STATIONS

PLATE 3

W907

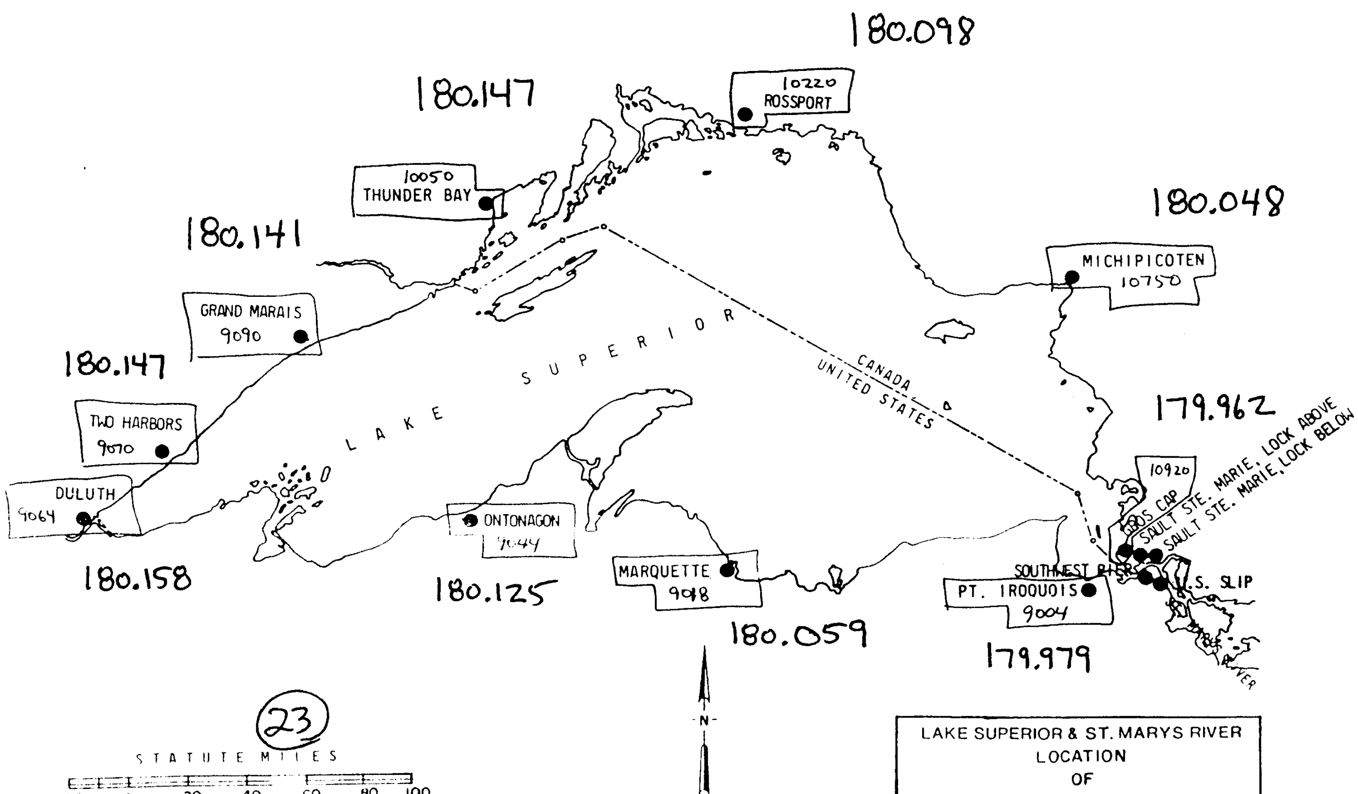


LAKES MICHIGAN AND HURON
LOCATION OF
WATER LEVEL GAUGING STATIOI


W908
173.510
7096
PORT INLAND
173.498
Mackinaw City
173.520
7072
STURGEON BAY CANAL
GREEN BAY
173.535
GREEN BAY
7078
LAKE MICHIGAN
7023
LUDINGTON
173.478
173.492
7057
MILWAUKEE
N
HOLLAND
7031
20 10 0
173.457
173.475
7044
CALUMET HARBOR

23

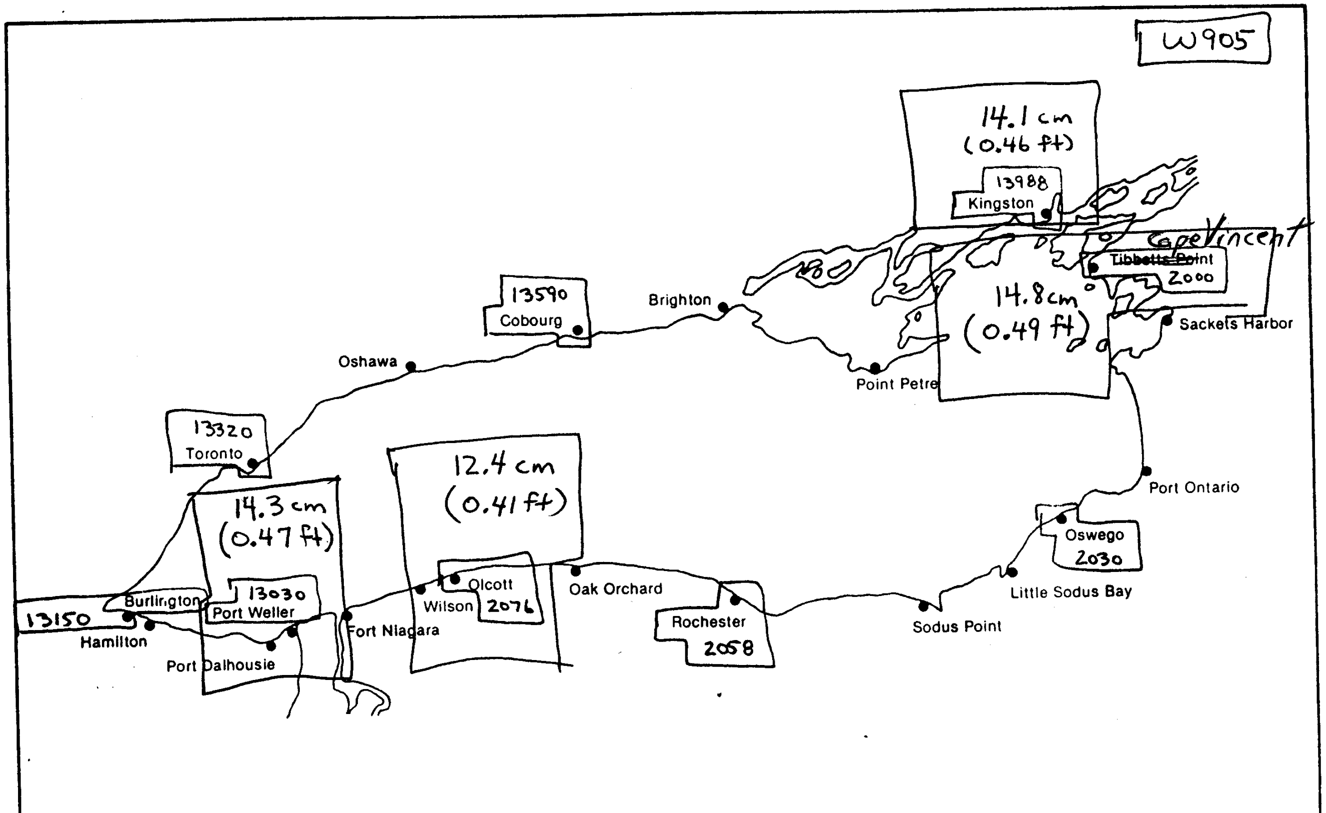
W909



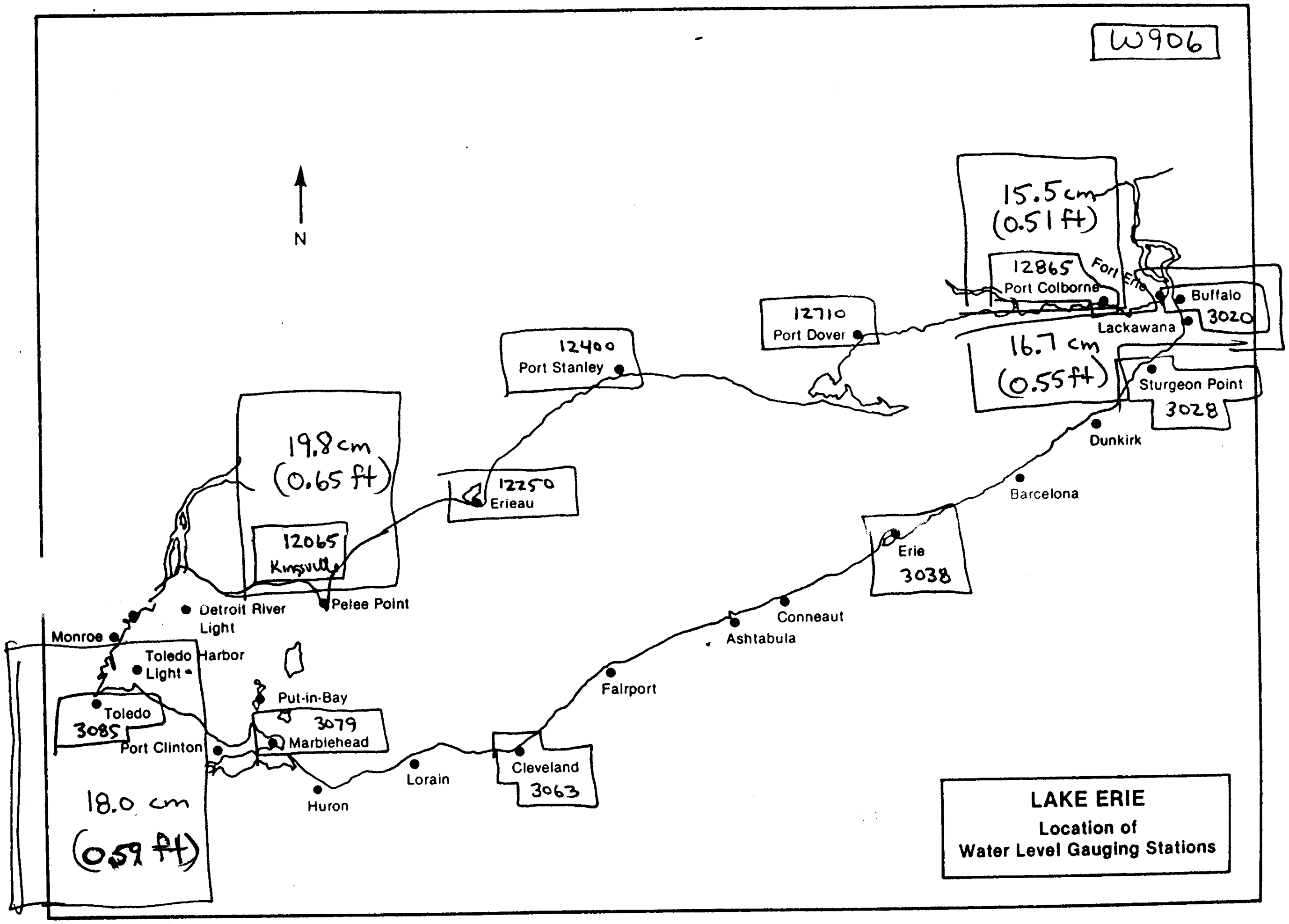
LAKE SUPERIOR & ST. MARYS RIVER
LOCATION
OF
WATER LEVEL GAUGING STATIONS

PLATE 1

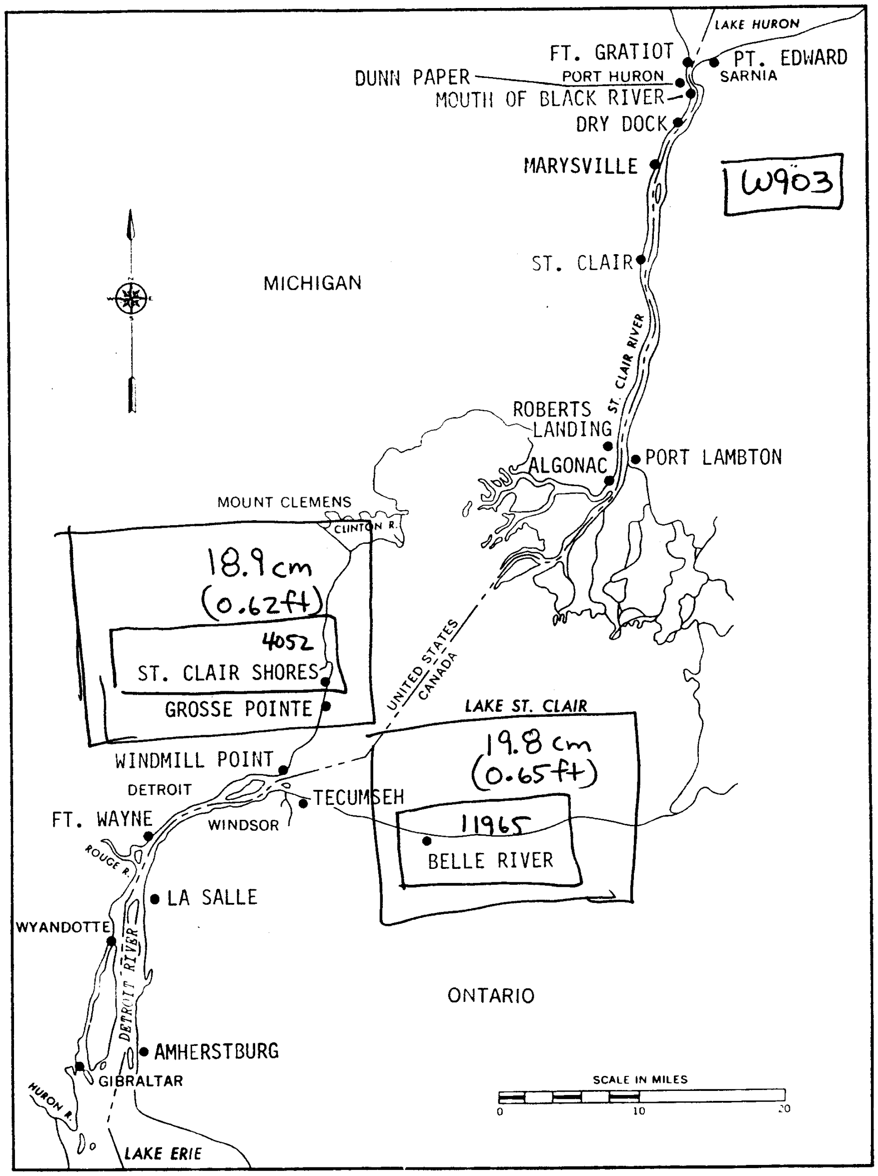
23



LAKE ONTARIO
Location of Water Level Gauging Stations



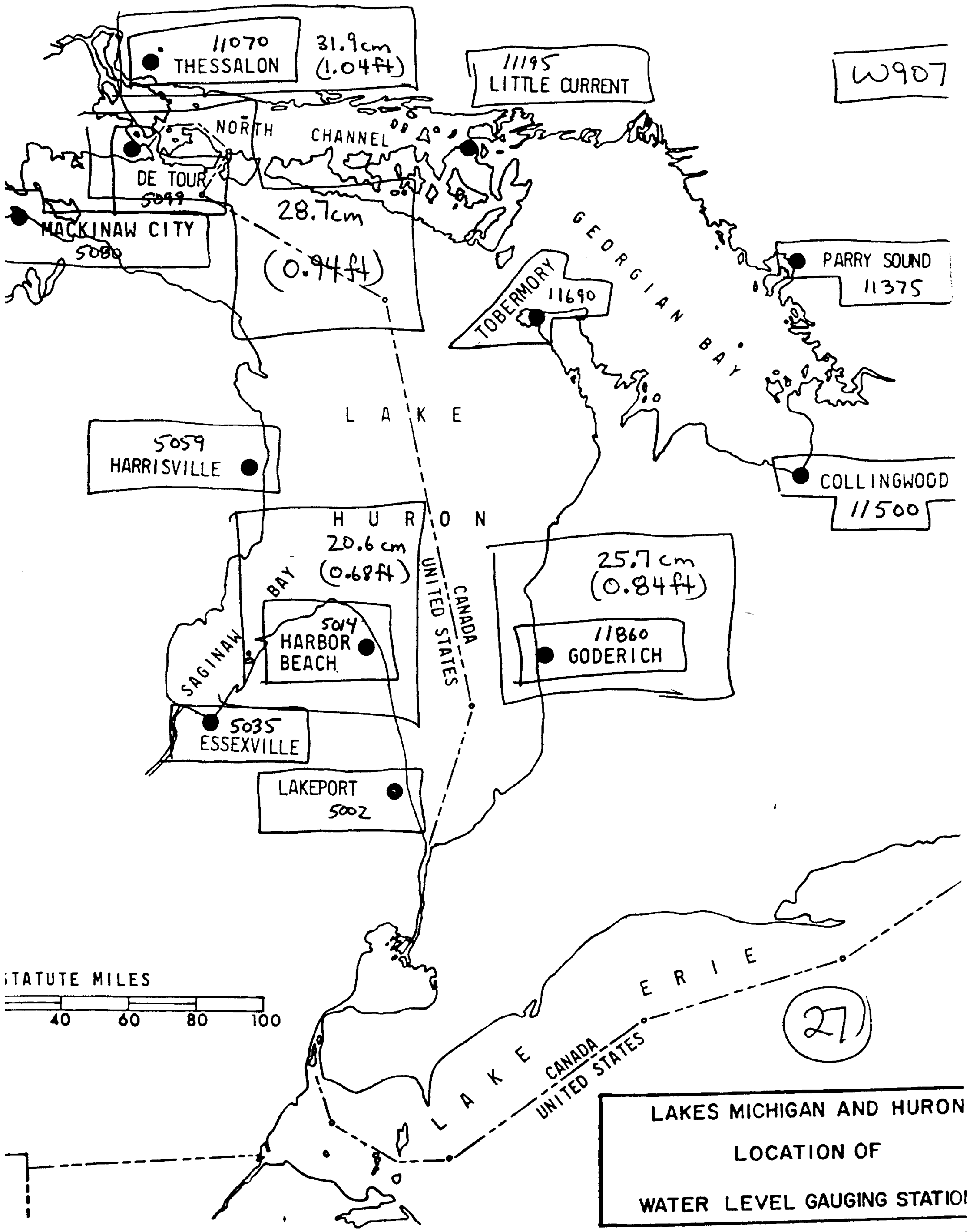
LAKE ERIE
Location of
Water Level Gauging Stations



ST. CLAIR - DETROIT RIVERS
LOCATION OF
WATER LEVEL GAUGING STATIONS

26

PLATE 3

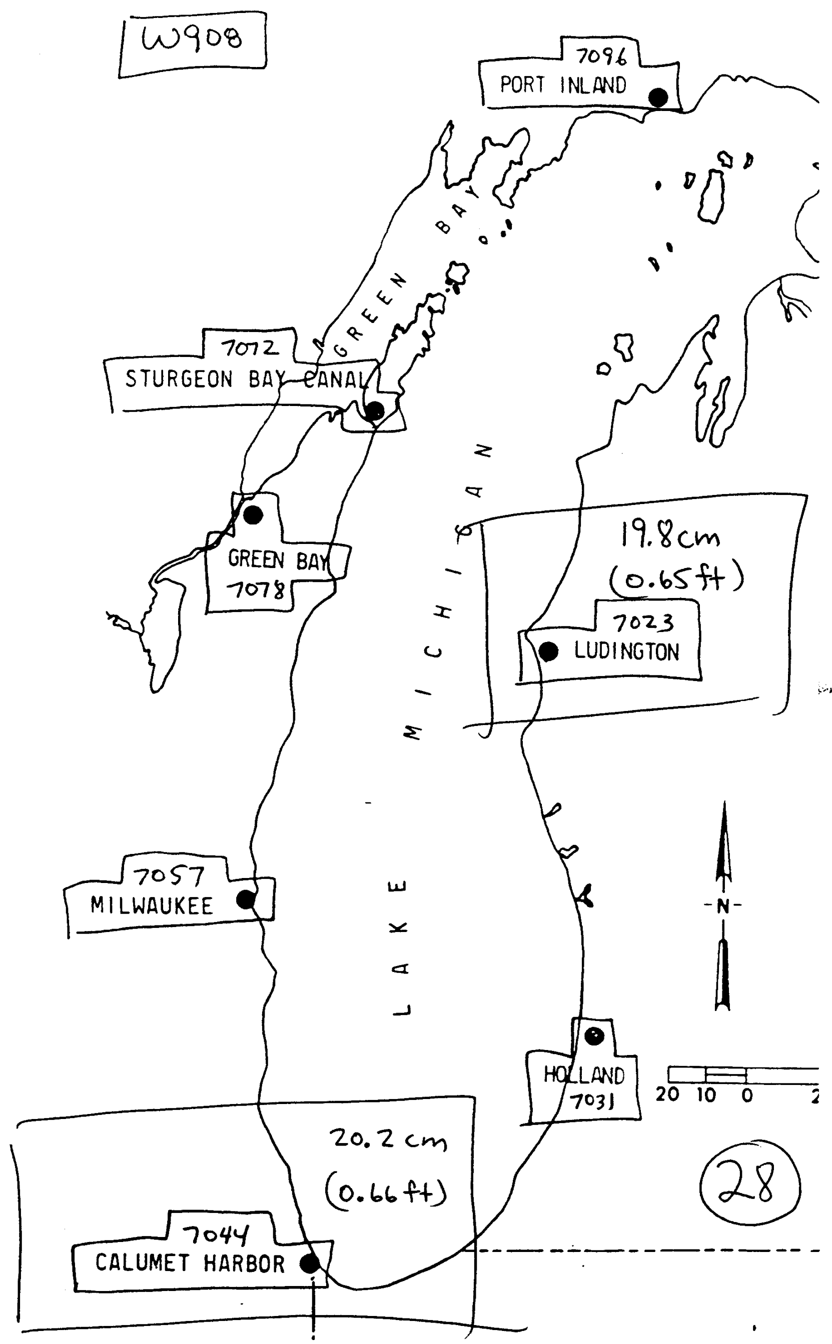


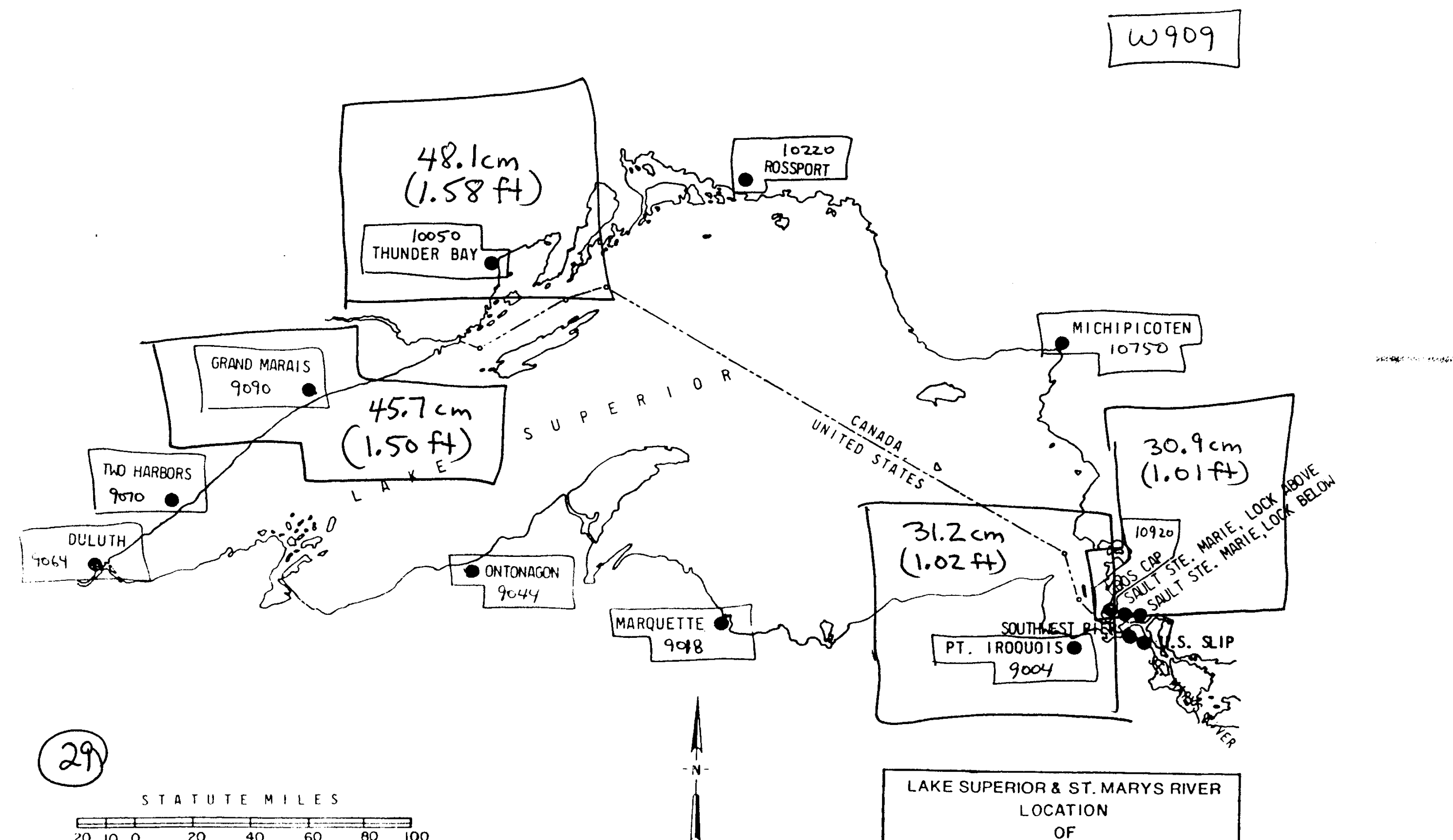
LAKES MICHIGAN AND HURON

LOCATION OF

WATER LEVEL GAUGING STATIOI

PLA


W908
7096
PORT INLAND
GREEN BAY
7072
STURGEON BAY CANAL
GREEN BAY
7078
LAKE MICHIGAN
19.8cm
(0.65ft)
7023
LUDINGTON
7057
MILWAUKEE
N
HOLLAND
7031
20 10 0
20.2 cm
(0.66 ft)
7044
CALUMET HARBOR
28



LAKE SUPERIOR & ST. MARYS RIVER
LOCATION
OF
WATER LEVEL GAUGING STATIONS

PLATE 1

filename: wp5\work_wp5\igld80.vl
Date: September 13, 1989